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香港科技大學
THE HONG KONG
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Edited By:

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The Hong Kong University of Science and Technology

Preface

The organizing committee of the 8th International Conference on Innovative Production and Construction (IPC 2020) and the Hong Kong University of Science and Technology gladly present the proceedings of the IPC 2020. The conference was held remotely in the purview of the then ongoing pandemic on the 7th and 8th December 2020, from Hong Kong.

The focus of IPC is technical and process-oriented innovations in the field of smart buildings and construction. The theme of IPC 2020 was "Advancement in Technologies and Processes for Smart Buildings and Construction" intended to cover a wide range in the field of technological advancements for the built environment. 16 prominent keynote speakers from leading academic organizations around the world had presented intellectually-stimulating keynote speeches related to the theme of IPC 2020. Researchers from different countries had met online to share the latest developments of their research in smart technologies for the architectural, engineering, construction, and operation (AECO) industry through a series of thematically organized parallel sessions. Research papers were submitted that went through two rounds of extensive peer review, performed by our scientific committee consisting of a pool of over 40 leading researchers in the field. The resulting proceeding is divided into the following groups:

- BIM-enabled AEC Applications
- Big Data and AI Learning
- Intelligent Construction Automation
- Risk and Safety Management in Construction
- Schedule and Cost Management

On behalf of the organizing committee, I hope that you find the IPC 2020 proceedings knowledge-inducing and enjoyable.

Dr. Jack C.P. Cheng
Chair, IPC 2020

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BIM-enabled AEC Applications

Extension of IFC Model Schema for Automated Prefabrication of Steel Reinforcement in Concrete Structures

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ABSTRACT: *Reinforced concrete (RC) is one of the most common types of materials used in building construction. Oftentimes, design optimization was performed at early stage to provide a clash-free layout for the steel reinforcement in RC frames. The BIM (Building Information Modeling) model is then generated in Industry Foundation Classes (IFC), an openBIM data format, and further converted to factory machine code format (in BVBS) for the automated prefabrication of steel reinforcement through some BIM software such as Tekla. Nowadays, engineers manually or semi-automatically generate the machine codes for rebar production in an ad hoc manner, which is also time consuming and error prone. In addition, data loss often occurs during the process of transforming the rebar BIM models to BVBS which leads to rebar prefabrication errors. Therefore, this paper presents an effective extension of IFC model schema for the rebar prefabrication process in order to cut down the frequency of manual intervention and boost the efficiency of data transforming. Firstly, with reference to Information Delivery Manual (IDM), rebar related IFC data containing key information about rebar are disassembled and reviewed within the data mapping specification with the aid of IFC viewers like Feature Manipulate Engine (FME). Then the requirement for attributes in BVBS data format are parsed with IFC model schema to obtain the pattern of mapping. Releasing of new entities in IFC are considered as well when mapping to ensure an accurate integration and conversion from IFC to machine code for prefabrication. A case study is used to illustrate the proposed method and some extensions are made to make up for the data loss and facilitate extension efficiency.*

KEYWORDS: *Building Information Modeling, Concrete Structures, Construction Automation, Industry Foundation Class, Prefabrication, Steel Reinforcement*

1. INTRODUCTION

The productivity of automated construction has been brought to the notice of the industry in Hong Kong since traditional reinforcement design with much manual intervention is more time-consuming and error prone. Besides, as stated in Construction Cost Handbook (2019), extremely limited space and high labor cost have always been a huge obstacle which chokes the development of construction. Hence, in response to this situation, digital fabrication emerges with better performance and saves more time and labor. Achieving a better performance on convenient and accurate information conveyance of building elements in the meantime, Collins (2016) mentioned that the benefits of digital models include clash detection in advance, confirmation of installation sequencing and validation of building component dimensions. And Marriage and Sutherland (2014) analyzed that there is increasing need for new systems of design, construction, and off-site prefabrication of higher efficiency, quality, speed and cost-effectiveness for the development of the construction industry.

According to Fitriawijaya, Tsai, and Taysheng (2019), Building Information Modeling (BIM) has become one of the biggest and standard platforms of digital construction so that designers could exchange information and perform collaboration on a shared model with each other. Architects could utilize it to simplify the information conversion within the design phases of the construction project, while structural and MEP engineers regard BIM as a powerful database to perform their design. Besides, Feng, Mustaklem and Chen (2012) studied that project engineers can obtain quantity takeoffs automatically and effectively through BIM. Several researches have been carried out on BIM-based digital fabrication and the information sharing system during the fabrication process, in which Industry Foundation Class (IFC) is an international openBIM standard and open data representation used to convey information of construction elements within comprehensive and iterative BIM process, as stated by Jaly-Zada, Koch and Tizani (2015). A knowledge-based approach has been proposed by Hamid, Tolba and Antably (2018) to integrate BIM objects with fabrication semantics to support the workflow between designers and fabricators through Computer Numerically Controlled (CNC) machines. And BIM data can be exchanged and shared among different participants in a building construction or facility management project. the

In Hong Kong, among all building elements, reinforcement occupies a large portion on total construction cost because Reinforced Concrete (RC) is one of the mostly used materials and reinforcing bar is responsible for essential structural functionality. Offsite prefabricated reinforcement production has been proposed to adapt to limited space in construction sites in Hong Kong. Not just money and time will be saved, but the overall productivity of construction elements' installment will also be benefitted and enhanced in a large degree if only rebar can be produced automatically offsite with cuts and bends. Aiming at productive offsite reinforcement prefabrication, reinforcement data input into the rebar cutting and bending machines must be complete enough to cover all details like identification and geometrical information.

In terms of fabrication, the productivity will be enhanced if fabrication machines could execute cutting and bending instructions correctly based on the parameters of rebars. Mainly focused on 2D drawings, BundesVereinigung der Bausoftware (BVBS) format is a numerical data structure developed for most types of fabrication machines to perform rebar cutting and bending, which is readable for rebar machine, as illustrated by Maciel and Corrêa (2016). It's in the form of a string composed of different blocks, each of which contains certain information like identification and geometrical data. However, IFC does not contain all information needed in BVBS specification, and the problem of missing attributes will be addressed through the data mapping among IFC, BVBS and some other BIM-authoring tools. And according to the updated IFC4Add2 documentation, new entities and new attributes under existing entities will be added to the IFC schema. Committed to seamless rebar fabrication, IFC files with key parameters of reinforcing elements will be converted to BVBS data format based on extended IFC schema, and this paper will present a use case using Dynamo in Revit to illustrate the whole process of conversion.

2. METHODOLOGY

Carrying semantic information of reinforcement elements, IFC files generated from BIM models could be viewed and parsed with the assistance of IFC viewers such as GeometryGym. In this tree view structure of IFC for one specific reinforcing bar shown in Fig 1, parameters like placement, grouping, definition and related structure are shown in different layers since the while IFC schema provides a clear hierarchy for entities in the documentation.

Fig. 1: Tree view of IFC file

According to the shape type and nature of rebars, BVBS specification can be classified into five main categories to be recognized as a certain group: BF2D (Two-dimensional rebar), BF3D (Three-dimensional rebar), BFWE (Spiral links), BFMA (Mesh) and BFGT (Lattice girders). Since BVBS mainly focuses on 2D rebar, two-dimensional rebar will be discussed mostly at this stage and a little bit about three-dimensional rebar will be mentioned as well.

In addition to shape type groups, the BVBS data format can be divided into different blocks each of which is responsible for defining different properties and most of them can be represented by one or two capital letters. The blocks are displayed as followed: Header Block (H), Geometry Block (G), Checksum Block (C), Chair Mesh Block (A), Bar Block(X/Y) and Private Block. The former three blocks are more frequently used because after lots of times of trying in BIM software to generate BVBS data structure, the latter three rarely appeared in the outcome. Thus, mainly parameters in Header Block (H), Geometry Block (G) and Checksum Block (C) will be discussed in this paper.

Fig. 2: Detail of BVBS specification

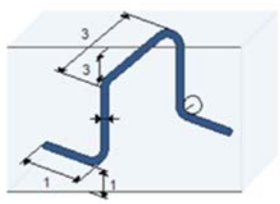

Fig. 3: Example of three-dimensional rebar

Details of attributes of BVBS and some examples of BVBS strings are shown in Fig 2. Each attribute starts with a lower-case letter such as j and i, and ends with a terminator "@". Header Block (H) covers all the identification information and characteristic attributes of reinforcement such as bar length, amount, diameter, steel grade and bending diameter which are always shown in the annotation of drawings. Geometry Block (G) involves the geometrical representation of rebars, which uses different coordinates in different rebar shape types: Polar coordinates for two-dimensional rebar and Cartesian coordinates for three-dimensional rebar. For the string of two-dimensional rebar which starts with BF2D, segment /leg length (l) and angle of following bend (w) are used. For example, the BVBS format for a two-dimensional rebar in the shape of Fig 3 can be represented as shown in the last line in Fig 2. A BVBS string of three-dimensional rebar directly uses Cartesian coordinates X, Y and Z to show the global locations of the ends of different segments/legs so that the bending machine can produce corresponding bends between two segments as required. Through Unicode encoding, Checksum Block (C) exhibits a checksum value g generated based on the BVBS substring before the Checksum Block (C), and main calculation loop in the C# code is shown in Fig 4.

Fig. 4: Process of calculating checksum value in C#

Model View Definition (MVD) is a subset of IFC schema and could be used to define information exchange, the requirement of which is specified though Exchange Requirement (ER), between stakeholders from different phases for a specific flow. Supported by IFC models, MVD may vary according to target software packages as the result of incorporation of information semantics and different aspects of supply chain according to Aram, Eastman, Venugopal, Sacks and Belsky (2013). MVD containing ER for reinforcing bar has been developed in Precast Concrete BIM Standard Documents shown in Fig 5. Representing and verifying ER, Information Delivery Manual (IDM) offers a universal and standardized method for information exchange as stated by Pinheiro, Corry, Kenny and O'Donnell (2015), and it consists of four major deliverables: a use case, the participates, the information contents and the process map which is created by using standard Business Process Modeling Notation (BPMN) templates.

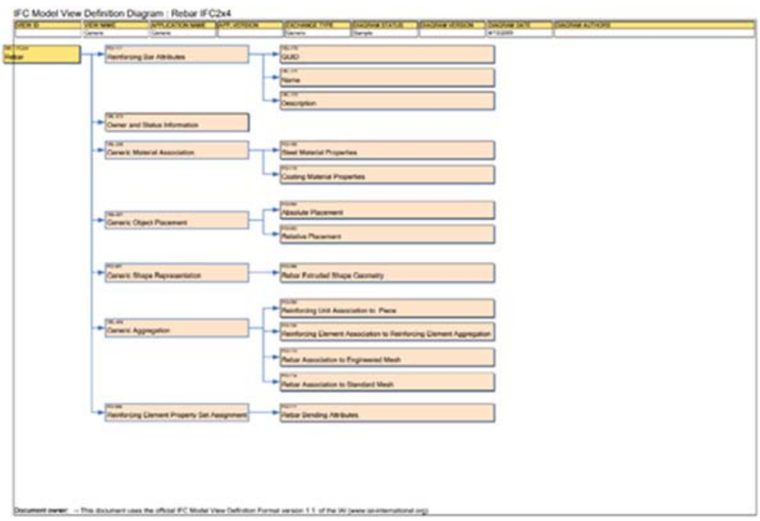

Fig. 5: Rebar MVD

Storing all information of construction elements inside, IFC can offer most of the data needed for prefabrication and BVBS as well. Relevant information could be extracted and provided by IFC and converted to BVBS format for further prefabrication. In order to achieve a better performance in prefabrication, the process of converting IFC file, which can be generated from BIM-authoring software like Revit and Tekla, to BVBS data format, requires accurate and efficient information extraction. A data mapping diagram between the most updated IFC4Add2 and

BVBS has been made to reveal the relationship of these two specifications and the reinforcement related working flow of IFC inheritance. However, data loss often occurs during the process and leads to prefabrication errors in rebar cutting and bending. Hence, an extended IFC schema is necessary to compensate missing data and perfect the transferring process from IFC to BVBS. And a case study will be presented to help to assist the illustration of extended IFC schema.

3. IFC EXTENSION

3.1. Data mapping between BVBS, IFC, Revit and Allplan

A data mapping chart (Fig 6) was made to clarify different attributes of reinforcement and locate missing information. Because BVBS mainly focuses on two-dimensional rebars, only attributes in header block, geometry block and checksum block in BVBS specification will be considered in the data mapping chart. More details about interoperability between BVBS and IFC4Add2 will be revealed in the following section.

As for Reference View and Design Transfer View exported from Revit in the most updated IFC4 versions, there are not many differences as far as the IFC file for the model for reinforcement. There is no *IfcReinforcingBarType*, but there is *IfcReinforcingBar* instead which covers bar length, nominal diameter and steel grade. In Revit, Dynamo was applied to assist extracting information from Revit models. Almost all attributes can be drawn except mass unit and angle following bends. Mass unit is only seen in BVBS but can be calculated and derived from existing data, and angle following bends could be calculated as well according to the definition of different shapes based on local reinforcement standard. In terms of Allplan, it includes all data needed for BVBS inside the parameters of rebars but mass unit just like IFC and Revit.

BVBS		IFC4				Revit(Dynamo)	Allplan
		IFC4Add2-TC1		IFC4 RV& DTV from Revit			
Attributes	Block	Entity	Attributes	Entity	Attributes	Attributes	Attributes
Two-dimensional rebar(BF2D)	**Shape Type Group**: recognition code	Mainly 2D rebars and Specific to Rebar Shapes		Mainly 2D rebars and Specific to Rebar Shapes		Mainly 2D rebars and Specific to Rebar Shapes	Mainly 2D rebars and Specific to Rebar Shapes
Three-dimensional rebar(BF3D)							
Spiral links(BFWE)							
Mesh(BFMA)							
Lattice girders(BFGT)							
Project Number(j)	**Header Block (H)**: provides data about identification and characteristics of the rebar	External Document		External Document		Input mannually	Input mannually
Drawing Number(r)							
Revision Number Index(i)							
Position(p)		IfcElement	Tag	\	\	Rebar Number	Mark Number
Length(l)		IfcReinforcingBarType	BarLength	IfcReinforcingBar	Bar Length(Optional)	Total Bar Length	Length
Amount(n)		IfcElementQuantity	Quantities	\	\	Quantity	Number of Pieces
Mass Unit(e)		**Derived from and Specific to Rebar Shape and Steel Grade**		\	\	**Derived from and Specific to Rebar Shape and Steel Grade**	\
Diameter(d)		IfcReinforcingBarType	NominalDiameter	IfcReinforcingBar	NominalDiameter(Optional)	Bar Diameter	Diameter
Steel Grade(g)		IfcReinforcingElementType	HasAssociation	IfcReinforcingBar	SteelGrade(Optional)	Material	Steel Grade
Bending Diameter(s)		IfcReinforcingBarType	BendingParameters	\	\	Bend Diameter	Bending Pin/Bending Pin Factor
Leg Length(l)	**Geometry Block (G)**: describes the rebar's shape bending geometry	IfcReinforcingBarType	BendingParameters	\	\	Dimensions	Segment Length
Angle of Following Bend(w)		IfcReinforcingBarType	BendingParameters	\	\	Derived from and Specific to Rebar Shape	Angle
Encoding needed	**Checksum Block (C)**: for a checksum value						
	Chair Mesh Block (A): defines the positions of the chain mesh in relation to bars						
	Bar Block(X/Y): used only to mesh for define a diameter, bar origins and length						
	Private Block: used for project or other internal data						

Fig. 6: Data mapping chart among different specifications and software

3.2. Extended data mapping diagram between existing IFC4Add2 schema and BVBS

A schematic IFC extension diagram was made based on the data mapping in previous work in terms of identification, characteristic properties, geometrical representation, steel grade, and quantities. In the up to date IFC4Add2 documentation, most of the parameters of *IfcReinforcingBar* have been transferred to a type-level entity:

IfcReinforcingBarType. It's worth mentioning that these attributes involved in identification of header block could not be obtained directly through IFC; instead, this type of information such as drawing number and revision index is offered by other external documents.

Aiming at achieving a seamless conversion from IFC to BVBS, some new entities and new attributes under existing entities are proposed to address and compensate missing information within the mapping. It has been noticed that only limited types of reinforcing elements including reinforcing bar, mesh and tendon are categorized under IfcReinforcingElementType. Thus, two new entities are proposed for other two kinds of reinforcing elements: reinforcing spiral and lattice girder. Listed in Fig 7, their attributes are proposed according to the attribute's arrangement for existing reinforcing element types.

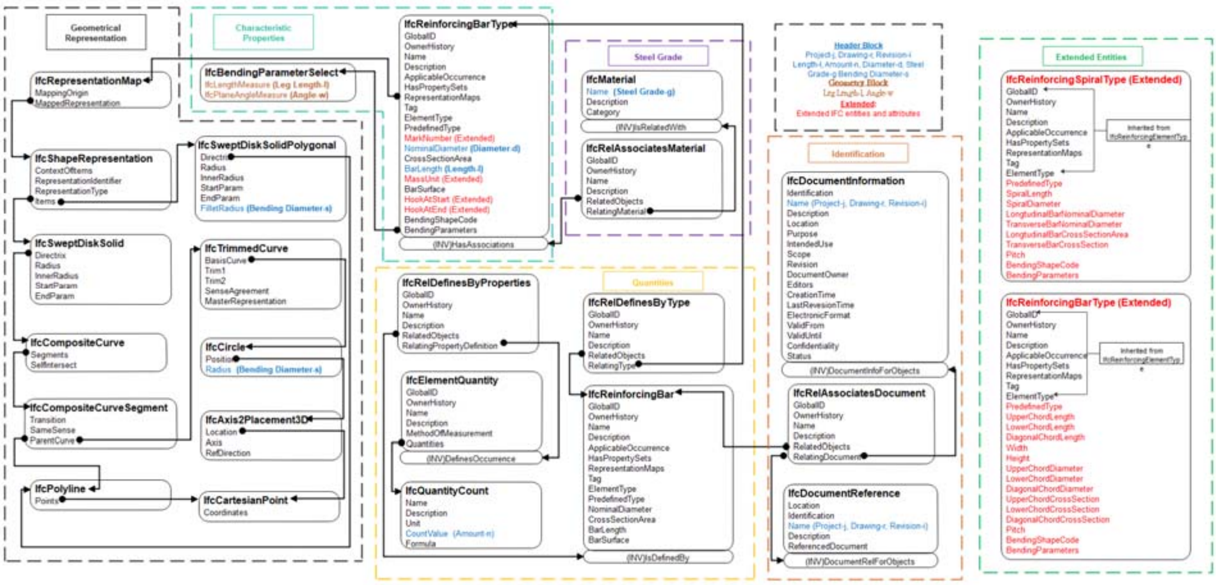

Fig. 7: Schematic diagram on IFC extension

4. USE CASE

Based on the extended IFC schema, this study tried to develop a robust BIM-based framework for automated generation of fabrication machine codes for automated rebar prefabrication. The software chosen is Dynamo in Revit, because Dynamo has customized nodes to perform certain functions like extracting required information for BIM models in Revit and there is Python complier built inside Dynamo so that users are able to write their own programs if existing nodes could not satisfy their needs.

Shown in Fig.8, a Dynamo program was developed to extract semantic and geometrical information from Revit models to generate BVBS files for fabrication. Firstly, the input can be all elements under the rebar category or selecting rebars as needed in the interface of Revit. And then, after selecting the elements, the program can almost obtain all parameters in Header Block through node *Element.GetParameterValueByName*. Among those which cannot be obtained from *Element.GetParameterValueByName*, identification parameters need to be input manually, and mass unit could be derived because of known density based on local code. As for geometry block, all segment length can be redefined and obtained and bending angle can be calculated accordingly. All these parameters will be arranged and composed based on the structure of BVBS specification, and the output will be exported to an external Excel Spreadsheet.

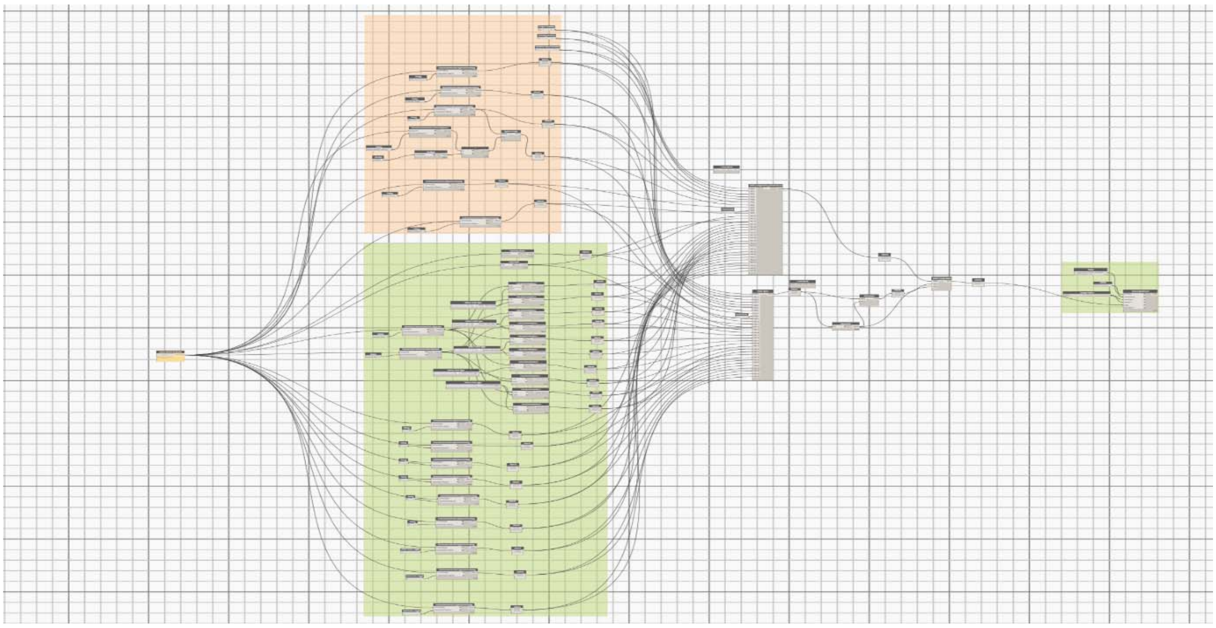

Fig. 8: Overview of Dynamo program

A clash-free solver is proposed to avoid clash in the circular column joint BIM model offered by Construction Industry Council (CIC) based on Generic Algorithm (GA). This study utilized this clash-free BIM model in Revit to illustrate the working process of this Dynamo program. Fig. 9 shows the BIM model and the tree view of its IFC file. And the output is illustrated through Excel Spreadsheet in Fig. 10, which presents all geometrical and semantic information of reinforcing bars.

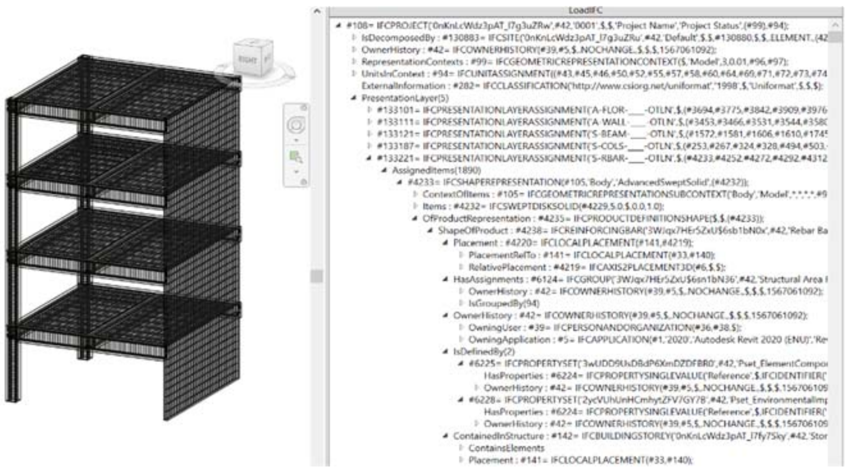

Fig. 9: BIM model generated from class-free solver

70	BF2D@HjP1@rL1@iL11@p14@l1422@n1@e0.561@d8@g500@s16@Gl56@w90@l1192@w-90@l496@w-90@l192@w-90@l496@w90@l56@w0@C87@
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93	BF2D@HjP1@rL1@iL11@p7@l1222@n1@e0.482@d8@g500@s16@Gl56@w90@l1292@w-90@l296@w-90@l292@w-90@l296@w90@l56@w0@C77@
94	BF2D@HjP1@rL1@iL11@p7@l1222@n1@e0.482@d8@g500@s16@Gl56@w90@l1292@w-90@l296@w-90@l292@w-90@l296@w90@l56@w0@C77@
95	BF2D@HjP1@rL1@iL11@p7@l1222@n1@e0.482@d8@g500@s16@Gl56@w90@l1292@w-90@l296@w-90@l292@w-90@l296@w90@l56@w0@C77@
96	BF2D@HjP1@rL1@iL11@p7@l1222@n1@e0.482@d8@g500@s16@Gl56@w90@l1292@w-90@l296@w-90@l292@w-90@l296@w90@l56@w0@C77@
97	BF2D@HjP1@rL1@iL11@p7@l1222@n1@e0.482@d8@g500@s16@Gl56@w90@l1292@w-90@l296@w-90@l292@w-90@l296@w90@l56@w0@C77@
98	BF2D@HjP1@rL1@iL11@p7@l1222@n1@e0.482@d8@g500@s16@Gl56@w90@l1292@w-90@l296@w-90@l292@w-90@l296@w90@l56@w0@C77@
99	BF2D@HjP1@rL1@iL11@p7@l1222@n1@e0.482@d8@g500@s16@Gl56@w90@l1292@w-90@l296@w-90@l292@w-90@l296@w90@l56@w0@C77@
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102	BF2D@HjP1@rL1@iL11@p14@l1422@n1@e0.561@d8@g500@s16@Gl56@w90@l1192@w-90@l496@w-90@l192@w-90@l496@w90@l56@w0@C77@
103	BF2D@HjP1@rL1@iL11@p14@l1422@n1@e0.561@d8@g500@s16@Gl56@w90@l1192@w-90@l496@w-90@l192@w-90@l496@w90@l56@w0@C77@
104	BF2D@HjP1@rL1@iL11@p14@l1422@n1@e0.561@d8@g500@s16@Gl56@w90@l1192@w-90@l496@w-90@l192@w-90@l496@w90@l56@w0@C77@

Fig. 10: Outcome of Dynamo program

5. CONCLUSIONS AND FUTURE WORK

This study introduced a commonly used machine code BVBS used for rebar bending and cutting, and data mapping among different BIM specifications and software is presented to address missing information. An IFC extension is made based on the updated IFC4Add2 documentation to assist the conversion from IFC to BVBS in industrial practices. To illustrate the reliability of IFC extension, a Dynamo program is developed based on the extended IFC schema to extract semantic and geometrical information from reinforcing bars of BIM models which has gone through class-free treatments, and further generate BVBS files. However, some problems remain to be solved in the conversion because of insufficient rebar-related database in Revit, and a lack of standardized rebar shape code makes it more difficult and confusing due to the need to predefine segments. And in the future IFC may be utilized to generate machine code BVBS so that all BIM-authoring software could participate in the fabrication process.

6. ACKNOWLEDGEMENT

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Cost Analysis of Geometric Quality Assessment of Structural Columns Based on 3D Terrestrial Laser Scanning

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ABSTRACT: *Terrestrial laser scanning (TLS)-based geometric quality assessment (QA) of construction components has been researched and utilized in recent years, which possesses a great potential to increase the QA accuracy and reduce superfluous labour. However, the economic applicability to use the TLS for geometric QA in the industry has not been assessed. Therefore, the quantitative cost benefits of TLS technology for geometric QA are not clear. In order to provide the construction industry with an instructive analysis to adopt the TLS technology in geometric QA, an investigation based on a comparative study is conducted. This study aims to quantitatively research the cost effect of TLS-based geometric QA for structural columns. The processes of the conventional approach with a total station, TLS-based approach with manual data analysis, and TLS-based approach with automated data analysis are first defined. Then, cost data from a case study are collected and processed in both project and company levels. The values of cost efficiency are calculated for analysis and comparison. By analyzing the result, it is demonstrated that the TLS-based approach with automated data analysis is more cost-beneficial in the long term. It is also indicated that compared to purchasing a TLS, renting a TLS are more economic for geometric QA. Thus, it can be stated from this study that the TLS technology has the potential to become an economical approach in a long-term consideration for a company. In addition, this study can help the industry practitioners to make an informed decision that suits their own case.*

KEYWORDS: *Geometric quality assessment, Terrestrial laser scanning, Information technology, Cost efficiency*

1. INTRODUCTION

In the construction industry, construction quality is one of the pillars to achieve the overall success of any project and has been a key issue since the late 1980s (Low and Ong, 2014). To ensure the success of construction projects, quality assessment (QA) is implemented to prevent potential problems from occurring by identifying the deviations of the as-built construction products based on certain quality requirements. What should be noticed is that, the structural works can cause major negative effects if the geometric quality is below standard requirements. Structural columns, especially, are the most essential structural works and are typically designed to carry gravity load and forces caused by lateral loading effects (Xiao, 2019). Therefore, it is necessary to ensure that the geometric quality of structural columns conforms to their design specifications.

The process of geometric QA can be separated into three main steps: QA data collection, QA data processing and QA data analysis (Anil et al., 2013). The QA data collection aims to obtain the as-built geometry of the target on-site. Then, QA data processing organizes and manipulates the raw data into a standardized format that can be used for comparison with the as-designed geometry. Finally, the QA data analysis is conducted to identify the deviations between the as-built and as-designed geometries. However, current QA approaches mostly rely on manual inspection with traditional tools (Wang et al., 2016a), and many researchers have highlighted the limitations of these manual approaches in both efficiency and accuracy. Realizing the problems of the current manual QA approaches, researchers proposed to apply 3D terrestrial laser scanning (TLS) technology on geometric QA, which has the characteristics of fast speed and high accuracy in acquiring measurement data (Wang et al., 2016a). However, such manual data analysis is still time-consuming. Therefore, researchers proposed some techniques to enhance the degree of automation and improve the accuracy in discrepancy measurement (Kim et al., 2014, Kim et al., 2016, Wang et al., 2016a, Oskouie et al., 2016, Wang et al., 2016b, Wang et al., 2017). It is proved that automated QA techniques can reduce the labour and time needed for QA, intensify the structuration and digitalization of construction information, and improve the overall project efficiency. Nevertheless, very few research efforts have been made to investigate the actual cost benefits of 3D TLS for geometric QA of construction components in a quantitative way.

This paper aims to fill this research gap by providing cost analysis of TLS-based geometric QA for structural columns. Based on a case study, this paper compares three geometric QA approaches include conventional approach with a total station, TLS-based approach with manual data analysis, and TLS-based approach with automated data analysis. Process of each approach is identified first to breakdown the work as tasks to define the time and cost. Then, cost analysis is conducted considering both project-level and company-level to proceed a comprehensive research under different circumstances. Through this research, researchers and industry practitioners can have a distinct understanding of the quantitative benefits of TLS on geometric QA for structural columns and help them to make an informed decision that suits their own case.

2. METHODOLOGY

To provide a comparative study to determine when and how the TLS-based geometric QA approach is worth implementing, this study compares TLS-based QA with conventional QA with a total station. Furthermore, for TLS-based QA, the QA data analysis can be conducted by either manual identification of deviations or automated identification of deviations with automated computer programs. Therefore, this study considers two different TLS-based QA approaches with either manual data analysis or automated data analysis. In summary, this study compares the cost of three different QA approaches: conventional approach with a total station (Approach 1), TLS-based approach with manual data analysis (Approach 2), and TLS-based approach with automated data analysis (Approach 3).

To perform cost analysis for the three approaches, this study is conducted in the following four steps based on a case study. As shown in Fig. 1, the detailed tasks for each QA approach are first defined, which include preparation, QA data collection, QA data processing and QA data analysis. Then, cost information of each task in each QA approach is collected from the case. In addition, to quantify the labour cost in each step, the time information is also collected. Next, the collected raw information is processed to facilitate further analysis. Lastly, cost analysis is performed with the processed data considering different gross floor areas (GFA) of a project or different numbers of projects constructed by a company.

2.1. Processes of three QA approaches

2.1.1. Approach 1: Conventional approach with a total station

As shown in Fig. 1, the general process of Approach 1 begins with locating control points on-site by a total station. Then the axes are set out on the ground by connecting the control points using an ink line marker. Once the preparation works are completed, the QA data collection is conducted to measure and record the as-built positions of structural columns as the distances from the columns to the nearest axes. In QA data processing, the recorded data are sorted out and input to Autodesk AutoCAD for further processing. Lastly, in QA data analysis, the as-built positions of columns are compared to the as-designed positions in AutoCAD, and the deviations are manually measured in AutoCAD and recorded in an Excel spreadsheet.

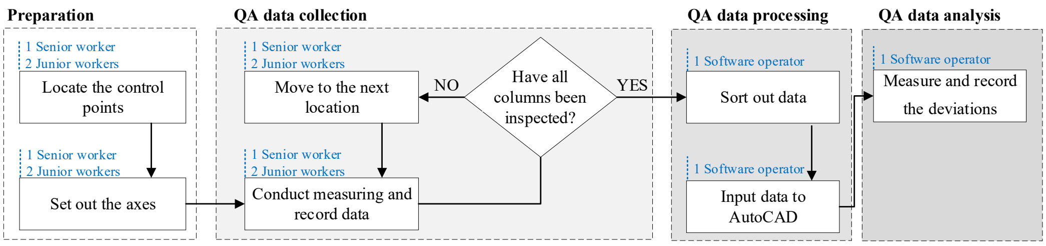

Fig. 1: Geometric QA process for Approach 1 (i.e. conventional approach with a total station)

2.1.2. Approach 2: TLS-based approach with manual data analysis

As shown in Fig. 2, Approach 2 starts with creating a scanning plan based on the site drawings. A scanning plan is created to determine the locations and sequence of scans, and determine the scanning parameters. The other preparation work is to set out the control points to facilitate the alignment of scan data and BIM model. After the preparation works, QA data collection is conducted to collect the laser scan data of the columns according to the scanning plan. For each scan, the TLS should be set up before conducting scanning. In QA data processing, the collected data are processed in the data processing software provided by the TLS vendor. Lastly, in QA data analysis, the registered scan data are aligned with the BIM model of the project based on control points in Autodesk

Navisworks. Then, the deviations of column positions are manually measured as the distances from as-designed columns to as-built ones using the measurement tool in Autodesk Navisworks.

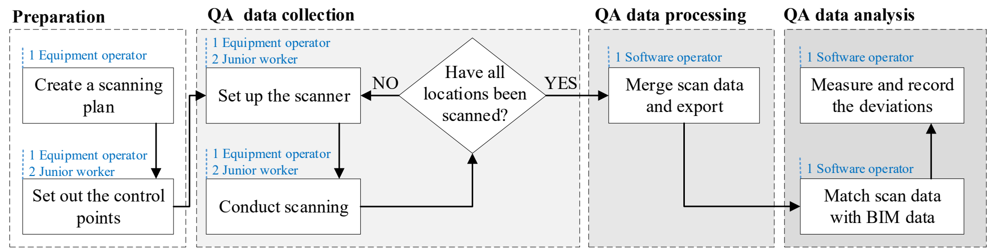

Fig. 2: Geometric QA process for Approach 2 (i.e. TLS-based approach with manual data analysis)

2.1.3. Approach 3: TLS-based approach with automated data analysis

Approach 3 (TLS-based approach with automated data analysis) shares the same steps of preparation, QA data collection and QA data processing as Approach 2. As shown in Fig. 3, when it comes to QA data analysis, the obtained scan data are automatically analyzed using a pre-developed program in Autodesk Dynamo. The program can automatically generate a report with the position deviations of structural columns.

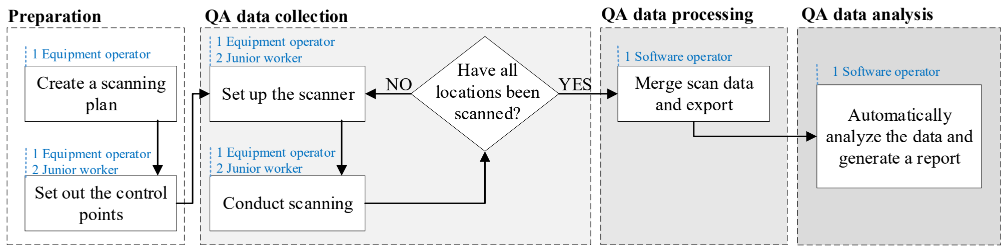

Fig. 3: Geometric QA process for Approach 3 (i.e. TLS-based approach with automated data analysis)

2.2. Case data collection

This step aims to collect data for three different QA approaches based on a real case. Time data are collected for all the tasks within the four steps of each QA approach. On the other hand, cost data are collected according to four categories: equipment, software, program development, and labor. Note that only the cost items that are directly involved in the geometric QA process are calculated. For equipment cost, the purchase and rental costs of the equipment are obtained through quotes from the local supplier by inquiry. The software cost is calculated based on subscribing based on the cost information from the corresponding official websites. As for labor cost, the number and types of workers for each task are identified first (as shown in Fig. 1-3), and then the wage of each labor type is obtained based on the average wage in the local industry.

2.3. Case data processing

This stage aims to process the raw case data so that the case data can be extended to a more general scenario. The cost is processed on both the project level and the company level. For the QA cost on project level, the total cost includes both fixed and variable costs. The fixed cost C_f^p (Singapore Dollars - SGD) does not change when the project GFA changes while the variable cost is heavily determined by the project GFA. When considering the QA cost on project level, all software and program are regarded as single-use and exclusive to this project, therefore, the costs of which are defined as fixed cost. As for labour cost, the classification of labour cost for a certain task is consistent with the classification of time data for the same task, which should be defined before. For the variable cost, the cost per unit area is denoted as C_{v1}^p (SGD/m^2). With regard to the equipment, the cost is classified as fixed cost when the equipment is accessed by purchase. With purchased equipment, the total cost C^p can be calculated as Equation (2.1). While if the equipment is rented for the project, the cost becomes variable cost because the rental term depends on project GFA. However, the rental cost of TLS is not exactly proportional to project GFA because TLS is rented on a basis of days. Instead, the rental cost is calculated based on the daily rental cost C_{v2}^p (SGD/day) and the renal term D (day). Here, the rental term D is calculated based on the project GFA, and is rounded up to the next integer (e.g. 10.1 days are rounded to 11 days). Therefore, the total QA cost C^p (SGD) of a project when the TLS is accessed by rent is calculated as Equation (2.2).

$$C^p = \begin{cases} C_f^p + C_{v1}^p \times GFA, & if\ purchase\ a\ TLS \quad (2.1) \\ C_f^p + C_{v1}^p \times GFA + C_{v2}^p \times D, & if\ rent\ a\ TLS \quad (2.2) \end{cases}$$

For the QA cost on company level, it is assumed that a company adopts a certain QA approach in a number of projects in the long term. To simplify, it is assumed that the QA approach is implemented on N projects with the same GFA as the case study project. The QA cost on company level contains both fixed and variable costs. The fixed cost C_f^c (SGD) does not increase as N increases while the variable cost is proportional to N and the cost per project is C_v^c (SGD/project). From the long-term perspective, the items that are not reusable or cannot be purchased as permanent properties are classified as variable cost, such as the labour and software cost. For equipment cost, the purchased equipment is regarded as fixed cost while a rented one is counted as variable cost. Though the development fee of program for automatic data analysis is a fixed cost, maintenance cost is needed when the program is adopted for more projects. Therefore, the maintenance cost of the developed program becomes a variable cost. Equation (3) shows the calculation of the total QA cost C^c (SGD) on company level:

$$C^c = C_f^c + C_v^c \times N \quad (2.3)$$

2.4. Case data analysis

According to the corresponding equations and data, the total cost of different QA approaches are predicted and calculated. In addition, to measure the degree of cost efficiency with the change of GFA or number of projects, auxiliary indicator to calculate cost efficiency E_c (m^2/SGD) is calculated as follows:

$$E_c = \frac{Q}{C}, \tag{2.4}$$

where Q is the total project GFA, C is the total QA cost. Therefore, the lower the total cost for a specific GFA, the higher the efficiency. These indexes help to choose a high-efficiency approach to create higher productivity and value for contractors.

3. CASE STUDY

3.1. Case description

The project chosen as the case study was undertaken at a construction site of a pet farm in Singapore with 4,200 m^2 GFA and 120 structural columns. The project was implemented by the contractor, who was keen to adopt TLS in their projects. Engineers from the VDC department of the contractor implemented the three QA approaches on the same site to collect the time data. A stopwatch was used to measure and record the time for QA data collection. Besides, a senior engineer of the contactor, who led the implementation of TLS-based QA, was interviewed to further collect other time and cost data.

3.2. Case data collection

3.2.1. Time data

The collected time data for three approaches are listed in Table 1. Then, To help classify the labour cost in each step, the classification of activity task was first conducted to differentiate the fixed time and variable time, which was shown in Table 3.

3.2.2. Cost data

Costs of the required items in every tasks of three approaches were collected through interview and investigation, which were further summarized in Table 2. For equipment, the electronic total station costed 5,600 SGD, and the TLS with reference sphere set costed 65,920 SGD if purchased, while it costed 250 SGD/day if TLS was rented. For software, the subscribe cost for Autodesk AutoCAD was 325.98 SGD/month, while Autodesk Navisworks was 142.170 SGD/month (Autodesk, 2019). For program, the development fee of program developed on Autodesk Dynamo (including subscription of Autodesk Dynamo) was 5,000 SGD. Because of the potential bugs and errors of the developed program, the maintenance cost was set as 80 SGD/project (Guimaraes, 1983) when considering QA cost on company level. For the labour cost, the hourly wage for a junior worker was 5.08 SGD/h while for senior worker was 13.15 SGD/h. The hourly wages for an equipment operator and a software operator were both 17.930 SGD/h.

3.3. Case data processing

3.3.1. Based on a single project

On the basis of collected cost data in Section 3.2.2 and the processed time data in Section 3.3.1, Table 4-6 summarize the cost data for three QA approaches on project level, respectively. Fixed costs are in SGD while variable costs are in SGD/100m2 or SGD/day. Because some items (e.g. software and equipment) were used in two or more than two tasks, the cost of the corresponding item was only calculated for the first time if it was fixed cost. This is why some cost items were zero, as shown in Table 4-6. Besides, because the duration of rental for a TLS was calculated in days, the number of renting days was estimated based on eight-hour day.

3.3.2. Based on a company

The cost data processed for company level were considered as long term cost. Therefore, only the costs of program development and equipment purchase were classified as fixed costs, while other items that were unable to become permanent properties were classified as variable costs for the company. Table 7-9 present the processed cost data for three approaches based on a company respectively.

4. RESULT AND ANALYSIS

This section compares the three QA approaches regarding QA time and cost by considering different GFA (project level) or different numbers of projects (company level). Furthermore, the three QA approaches were compared regarding the time efficiency E_t and cost efficiency E_c.

4.1. Based on a single project

Fig. 4(a) and 4(b) show the total costs and cost efficiencies of geometric QA for different project GFA. Considering both purchase and rental of TLS, a total of five QA approaches with different TLS options were compared. In general, Approaches 2 and 3 with purchased TLS had the highest costs due to high TLS purchase cost. On the other hand, rental-based Approaches 2 and 3 had the lowest costs, and Approach 1 ranked in the middle. Comparing the two rental-based approaches, rental-based Approach 2 had a lower cost than rental-based Approach 3 because of the initial development cost of program. Therefore, it can be concluded that, when considering of the geometric QA cost on a single project, rental-based Approach 2 was the most cost-efficient approach. With the increase of GFA, cost efficiency E_C for rental-based Approach 2 tended to be around 16 m^2/SGD and rental-based Approach 3 tended to be 10 m^2/SGD, while the E_C of Approach 1 would only reach the ceiling of 6 m^2/SGD.

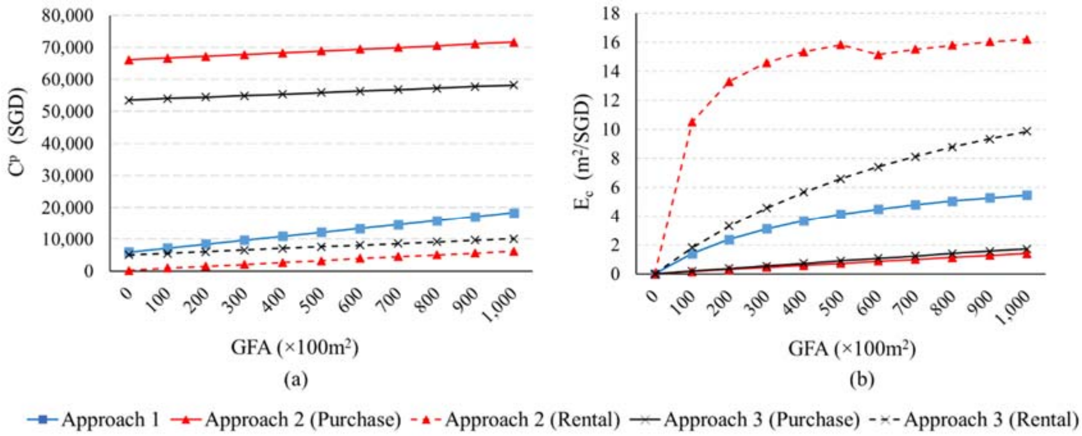

Fig. 4: Cost analysis for three QA approaches based on a single project: (a) Total cost of three approaches with different GFA of project, and (b) cost efficiency of three approaches with different GFA of project.

Table 1: Collected time data for geometric quality assessment for three QA approaches.

QA Process	Approach 1		Approach 2		Approach 3	
	Task	**Time (h)**	**Task**	**Time (h)**	**Task**	**Time (h)**
Preparation	Locate the control points	2.000	Create a scanning plan	0.500	Create a scanning plan	0.500
	Set out the axes	2.000	Set out the control points	0.100	Set out the control points	0.100
QA data collection	Conduct measuring and record data	6.000	Set up the scanner	0.050	Set up the scanner	0.050
			Conduct scanning	0.600	Conduct scanning	0.600
QA data processing	Sort out data	2.000	Merge scan data and export	8.000	Merge scan data and export	8.000
	Input data to AutoCAD	10.000				
QA data analysis	Measure and record the deviations	4.000	Match scan data with BIM data	2.000	Automatically analyze the data and generate a report	1.000
			Measure and record the deviations	2.000		

Table 2: Collected cost data of three QA approaches.

Cost type	Cost item	Cost category	Unit	Value
Equipment	Electronic total station	Purchase	SGD	5,600.000
	TLS and reference sphere set	Purchase	SGD	65,920.000
		Rental	SGD/day	250.000
Software	Autodesk AutoCAD	Subscribe	SGD/month	325.980
	Autodesk Navisworks	Subscribe	SGD/month	142.170
Program	Program developed on Autodesk Dynamo (including Autodesk Dynamo)	Development	SGD	5,000.000
		Maintenance	SGD/project	80.000
Labour	Junior worker	Wage	SGD/h	5.080
	Senior worker	Wage	SGD/h	13.150
	Equipment operator	Wage	SGD/h	17.930
	Software operator	Wage	SGD/h	17.930

Table 3: Time classification of three QA approaches based on tasks.

QA Process	Approach 1		Approach 2		Approach 3	
	Task	**Classification**	**Task**	**Classification**	**Task**	**Classification**
Preparation	Locate the control points	Variable time	Create a scanning plan	Fixed time	Create a scanning plan	Fixed time
	Set out the axes	Variable time	Set out the control points	Variable time	Set out the control points	Variable time
QA data collection	Conduct measuring and record data	Variable time	Set up the scanner	Variable time	Set up the scanner	Variable time
			Conduct scanning	Variable time	Conduct scanning	Variable time
QA data processing	Sort out data	Variable time	Merge scan data and export	Variable time	Merge scan data and export	Variable time
	Input data to CAD	Variable time				
QA data analysis	Measure and record the deviations	Variable time	Match scan data with BIM data	Variable time	Automatically analyze the data and generate a report	Variable time
			Measure and record the deviations	Variable time		

Table 4: Cost for Approach 1 based on a single project.

QA Process	Task	Cost type	Classification	Unit	Cost
Preparation	Locate the control points	Labour	Variable cost	SGD/100m^2	1.110
		Equipment	Fixed cost	SGD	5,600.000
	Set out the axes	Labour	Variable cost	SGD/100m^2	1.110
QA data collection	Conduct measuring and record data	Labour	Variable cost	SGD/100m^2	3.330
QA data processing	Sort out data	Labour	Variable cost	SGD/100m^2	0.854
	Input data to CAD	Labour	Variable cost	SGD/100m^2	4.269
		Software	Fixed cost	SGD	325.980
QA data analysis	Measure and record the deviations	Labour	Variable cost	SGD/100m^2	1.708
		Software	Fixed cost	SGD	0.000

Table 5: Cost for Approach 2 based on a single project.

QA Process	Task	Cost Type	Purchase			Rent		
			Classification	Unit	Cost	Classification	Unit	Cost
Preparation	Create a scanning plan	Labour	Fixed Cost	SGD	6.575	Fixed Cost	SGD	6.575
	Set out the control points	Labour	Variable cost	SGD/100m^2	0.043	Variable cost	SGD/100m^2	0.043
QA data collection	Set up the scanner	Labour	Variable cost	SGD/100m^2	0.027	Variable cost	SGD/100m^2	0.027
		Equipment	Fixed Cost	SGD	65,920.000	Variable cost	SGD/day	250.000
	Conduct scanning	Labour	Variable cost	SGD/100m^2	0.329	Variable cost	SGD/100m^2	0.329
		Equipment	Fixed Cost	SGD	0.000	Variable cost	SGD/day	250.000
QA data processing	Merge scan data and export	Labour	Variable cost	SGD/100m^2	3.415	Variable cost	SGD/100m^2	3.415
QA data analysis	Match scan data with BIM data	Labour	Variable cost	SGD/100m^2	0.854	Variable cost	SGD/100m^2	0.854
		Software	Fixed Cost	SGD	142.170	Fixed Cost	SGD	142.170
	Measure and record the deviations	Labour	Variable cost	SGD/100m^2	0.854	Variable cost	SGD/100m^2	0.854
		Software	Fixed Cost	SGD	0.000	Fixed Cost	SGD	0.000

Table 6: Cost for Approach 3 based on a single project.

QA Process	Task	Cost Type	Purchase			Rent		
			Classification	Unit	Cost	Classification	Unit	Cost
Preparation	Create a scanning plan	Labour	Fixed Cost	SGD	6.575	Fixed Cost	SGD	6.575
	Set out the control points	Labour	Variable cost	SGD/100m^2	0.043	Variable cost	SGD/100m^2	0.043
QA data collection	Set up the scanner	Labour	Variable cost	SGD/100m^2	0.027	Variable cost	SGD/100m^2	0.027
		Equipment	Fixed Cost	SGD	65,920.000	Variable cost	SGD/day	250.000
	Conduct scanning	Labour	Variable cost	SGD/100m^2	0.329	Variable cost	SGD/100m^2	0.329
		Equipment	Fixed Cost	SGD	0.000	Variable cost	SGD/day	250.000
QA data processing	Merge scan data and export	Labour	Variable cost	SGD/100m^2	3.415	Variable cost	SGD/100m^2	3.415
QA data analysis	Automatically analyze the data and generate a report	Labour	Variable cost	SGD/100m^2	0.854	Variable cost	SGD/100m^2	0.854
		Program	Fixed Cost	SGD	5,000.000	Fixed Cost	SGD	5,000.000

Table 7: Cost for Approach 1 based on a company.

QA Process	Task	Cost type	Classification	Unit	Cost
Preparation	Locate the control points	Labour	Variable cost	SGD/project	46.620
		Equipment	Fixed cost	SGD	5,600.000
	Set out the axes	Labour	Variable cost	SGD/project	46.620
QA data collection	Conduct measuring and record data	Labour	Variable cost	SGD/project	139.860
QA data processing	Sort out data	Labour	Variable cost	SGD/project	35.860
	Input data to CAD	Labour	Variable cost	SGD/project	4.269
		Software	Variable cost	SGD/project	325.980
QA data analysis	Measure and record the deviations	Labour	Variable cost	SGD/project	71.720
		Software	Variable cost	SGD/project	325.980

Table 8: Cost for Approach 2 based on a company.

QA Process	Task	Cost Type	Purchase			Rent		
			Classification	Unit	Cost	Classification	Unit	Cost
Preparation	Create a scanning plan	Labour	Variable cost	SGD/project	6.575	Fixed Cost	SGD/project	6.575
	Set out the control points	Labour	Variable cost	SGD/project	1.883	Variable cost	SGD/project	1.883
QA data collection	Set up the scanner	Labour	Variable cost	SGD/project	1.151	Variable cost	SGD/project	1.151
		Equipment	Fixed Cost	SGD	65,920.000	Variable cost	SGD/project	250.000
	Conduct scanning	Labour	Variable cost	SGD/project	13.806	Variable cost	SGD/project	13.806
		Equipment	Fixed Cost	SGD	0.000	Variable cost	SGD/project	0.000
QA data processing	Merge scan data and export	Labour	Variable cost	SGD/project	143.440	Variable cost	SGD/project	143.440
QA data analysis	Match scan data with BIM data	Labour	Variable cost	SGD/project	35.860	Variable cost	SGD/project	35.860
		Software	Variable cost	SGD/project	142.170	Fixed Cost	SGD/project	142.170
	Measure and record the deviations	Labour	Variable cost	SGD/project	35.860	Variable cost	SGD/project	35.860
		Software	Variable cost	SGD/project	0.000	Fixed Cost	SGD/project	0.000

Table 9: Cost for Approach 3 based on a company.

QA Process	**Task**	**Cost Type**	**Purchase**			**Rent**		
			Classification	**Unit**	**Cost**	**Classification**	**Unit**	**Cost**
Preparation	Create a scanning plan	Labour	Variable cost	SGD/project	6.575	Fixed Cost	SGD/project	6.575
	Set out the control points	Labour	Variable cost	SGD/project	1.883	Variable cost	SGD/project	1.883
QA data collection	Set up the scanner	Labour	Variable cost	SGD/project	1.151	Variable cost	SGD/project	1.151
		Equipment	Fixed Cost	SGD	65,920.000	Variable cost	SGD/project	250.000
	Conduct scanning	Labour	Variable cost	SGD/project	13.806	Variable cost	SGD/project	13.806
		Equipment	Fixed Cost	SGD	0.000	Variable cost	SGD/project	0.000
QA data processing	Merge scan data and export	Labour	Variable cost	SGD/project	143.440	Variable cost	SGD/project	143.440
QA data analysis	Automatically analyze the data and generate a report	Labour	Variable cost	SGD/project	17.930	Variable cost	SGD/project	17.930
		Program	Fixed Cost	SGD	5,000.000	Fixed Cost	SGD	5,000.000
			Variable cost	SGD/project	80.000	Variable cost	SGD/project	80.000

4.2. Based on a company

On the company level, the cost was calculated for different numbers of projects. The range of number of projects was from 1 to 100. The maximum number of 100 was determined assuming that a TLS could operate for 10 years and a company had 10 projects per year. As shown in Fig. 5(a) and 5(b), rental-based Approach 2 had the lowest cumulative cost and the highest cost efficiency within 50 projects. Nevertheless, when the number of projects was more than 50, rental-based Approach 3 revealed a higher cost efficiency and lower cumulative cost, as the labour cost savings from automated data analysis exceeded the program development costs. As indicated in Fig. 8, both purchase-based Approaches 2 and 3, however, were still inefficient on a company level even for 100 projects in a 10-year-operation. In general, Approach 1 was more efficient than purchase-based Approaches 2 and 3, and less efficient than rental-based Approaches 2 and 3. Therefore, rental-based Approach 3 would be the best choice in the long run with E_C reaching 7.4 m^2/SGD when the number of projects reached 100, while the E_C values for Approach 1 and rental-based Approach 2 were 5.8 m^2/SGD and 6.8 m^2/SGD, respectively.

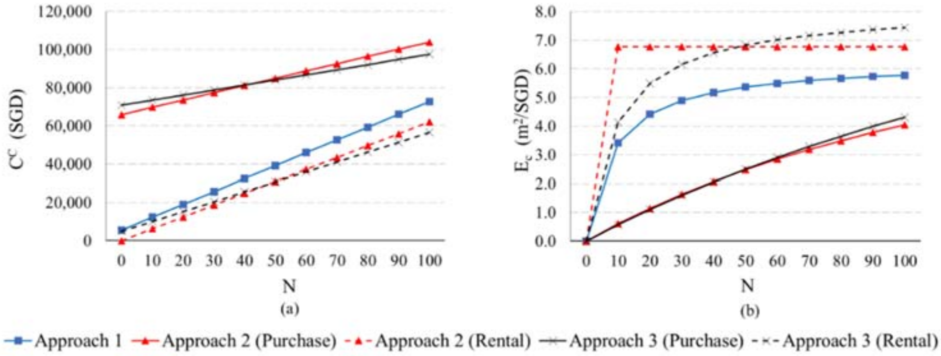

Fig. 5: Cost analysis for three QA approaches based on a company: (a) Total cost of three approaches with varying numbers of project, and (b) cost efficiency of three approaches with varying numbers of project.

5. CONCLUSION

This paper quantitatively investigated the performance of TLS-based geometric QA approaches by analysing the QA cost using a comparison study with a conventional approach. On account of the application status of laser scanning, the TLS-based approaches are divided into manual data analysis approach and automatic data analysis approach. The processes of the three proposed approaches are identified and the tasks are broken down at first. Then, a case study was researched to obtain the related time and cost data for each task. Interviews with engineers provided supplementary information of the case data. Next, the collected case data were processed to meet the requirement for later analysis. The cost data were processed at two levels, project level and company level, where the cost data were also classified as fixed cost and variable cost based on different levels. On project level, any involved cost items were considered as single-use. As for company level, the items which can be purchased as permanent properties are reused in the service lifetime. To figure out whether to purchase or rent the TLS, both purchase and rental options were considered in cost analysis. Lastly, a concept of efficiency is proposed to compare the performance of cost for different options.

The results demonstrated that the rental-based approach with manual data analysis was the most cost-efficient approach in terms of cost on project level. In addition, the upper limit of cost efficiency E_C of the conventional approach was 6 m^2/SGD, which was lower than TLS-based approaches. For cost on company level, in comparison with E_C of 5.8 m^2/SGD for the conventional approach and 6.8 m^2/SGD for rental-based approach with manual data analysis, the rental-based approach with automatic data analysis would be the best option in the long term and reached 7.4 m^2/SGD after 10-year-operation. Due to the high price of TLS, the cost efficiencies of purchase-based approaches on both project and company levels were quite low. The geometric QA in this study provided a motivating example to analyze the cost for TLS, and demonstrated the benefits of involving automatic information technologies. It can be stated from this study that the TLS technology has the potential to become an economical approach in a long-term consideration for a company. However, this study only quantitatively analyzed the cost benefits of TLS technology adopted in geometric QA. Future study will focus on the assessment of the environment impact, social impact and involved risk management of the adoption of TLS technology for geometric QA.

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A Framework for Semantic Interoperability of BIM and UAS Flight Mission Planning System

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ABSTRACT: *Building information modeling (BIM), as a database infrastructure, can manage a myriad of data on a project lifecycle entity. Particularly in the construction phase, BIM can help with encapsulating the numerous data for creating a more efficient and sustainable project control environment. Unmanned aircraft system (UAS) has been used for various purposes in the construction and infrastructure task environment. The UAS can capture visual images based on the determined flight mission. To develop the flight mission, the flight goals and parameters should be identified. However, the current planning systems require manual pilot-flights before developing the plan to identify the accurate flight parameters. Even if a satellite map is provided, it cannot provide the current conditions referring to the work progress and updated geological information. All components in a BIM model have geometry information based on the project-based coordinate system, and this can provide users with the UAS flight information. In this respect, data extracted from the BIM should be transmitted and mapped to the UAS flight mission planning system via semantically interoperable systems. The entire study will be able to develop an interoperable environment between one of the commercial flight mission planning applications and BIM. The main objectives of this paper are: (1) to identify the flight mission data which could be extracted from the BIM environment; and (2) to provide a framework of the semantically interoperable systems. This research will contribute to a better understanding of the interoperable environment between the UAS and the BIM, to facilitate the collaborative construction environment.*

KEYWORDS: *UAS (Unmanned Aircraft Systems), BIM (Building Information Modeling), Semantic Interoperability, and Data Exchange*

1. INTRODUCTION

Unmanned Aircraft Systems (UAS) commonly have increasingly been utilized for collecting visual data, such as still images or videos on construction and infrastructure work environments. The main objective of UAS operations is to collect visual images have geo-referenced information based on the Ground Positioning System (GPS) data and flight mission. The current way to develop the missions generally involves selecting the area to fly over on the general map of existing conditions in described applications that uses satellite imagery such as Google maps. It requires obtaining input data regarding geological information (e.g., area boundaries and maximum altitude or distance) as well as setting specific sensor parameters (e.g., forward and side overlap or resolution or the size of a single-pixel) for safe and effective operations. However, significant limitations are that the satellite maps used do not always have the latest conditions of the worksite and do not consider the current progress of constructions. The selection of the area in the map is made in 2D space and does not consider the elevation of structures or points of interest. Therefore, this method cannot directly provide users with intuitive flight parameters for developing the mission. Consequently, it makes the users have several pilot flights to capture the geological input data to develop the mission plans. Otherwise, the operations based on this current approach is only relying on the general environment shown on the map and does not consider the changes in the construction project over time. In the worst cases, the UAS would crash into the structure on-site since the flight plan does not consider the structures on the construction environments.

Building Information Model (BIM) can store the geometric and semantic information of all objective components, including building material, structure, surrounding environments on the relative coordination system. This system integrates the descriptions of all the visualized building objects and the related heterogeneous data during a project lifecycle entity. One of the prior studies has tried to develop the automated flight mission planning system in the BIM environment (Freimuth and König, 2015; Freimuth, Müller and König, 2017). This study contributed to developing the conceptual automated UAS based inspection system in the construction environment. However, this system and BIM environment are very cumbersome to update, coordinate, and facilitate since they may have a myriad database about all model components as well as the flight mission plan data (Sabol, 2008; Solihin et al., 2017; Solihin, Eastman and Lee, 2017). To mitigate this problem, this study will develop the semantic data interoperable environment between the UAS and BIM without the increase of data amount to be handled in the BIM. The UAS-based imagery captured during flight could be used to generate Three-Dimensional (3D) engineered data, such as point cloud, Digital Elevation Model (DEM), or Digital Surface Model (DSM) through photogrammetry process (Kim, Irizarry and Bastos Costa, 2016). UAS flight mission plans are usually required to operate the UAS in a safe and effective way. To generate accurate 3D data, it is recommended that the plans have appropriate image acquisition paths (grid or circle) and overlaps (frontal and side overlap) because points of interests would have complex geometry information. The underlying point cloud data can be imported into BIM applications and used for converting into a BIM object-based model (Hichri et al., 2012). It is interoperable between the UAS operations and BIM. This interactive data exchange system could also check the work progress or design changes by comparing the as-built model and the as-is model based on the object model generated from the point cloud data.

The primary goals of this research are to identify required dataset of both UAS and BIM for defining interoperability between them and to develop the BIM-data extraction system to be used on UAS flight mission planning for automated visual data collection of specific elements or areas within a construction site. The scope of this paper is to present an overall framework for the interoperable data process between the UAS and BIM, as well as a description of each step in the framework. This effort will aim to a better understanding of the interactive uses of UAS and BIM in construction work environments.

2. INTEGRATION OF BIM AND UAS APPLICATIONS

BIM is a tool as well as a process enabled to integrate a myriad of data for building components and their relationships (Arayici, Egbu, and Coates, 2012). As a database during the project life cycle, BIM can influence all stakeholders directly or indirectly by generating, utilizing and sharing the data (Eastman et al., 2011). BIM data is consumed for all stakeholders in many aspects such as energy consumption analysis (Azhar and Brown, 2009; Yan et al., 2013), structural analysis in design (Barazzetti et al., 2015), and structural evaluation during construction (Zhang and Hu, 2011) by obtaining necessary details from the integrated database (Jeong et al., 2016). Data interoperability, exchanging data between applications for collaboration and automation (Eastman et al., 2011), becomes important to have functionality for all stakeholders engaging different specific needs among integrated BIM data (McGraw Hill Construction, 2014). Data interoperability enables to pass data with other applications and eliminate wastes to reproduce data already generated in BIM (Eastman et al., 2011; Jeong et al., 2016). The buildingSmart® developed Industry Foundation Classes (IFC) format to support data interoperability for the construction industry (Karan and Irizarry, 2015). However, different definitions of building objects and their relationships between BIM and other systems can still cause the lack of data interoperability and lack of semantic interoperability, exchanging data with shared meaning, between different systems (Eastman et al., 2011; Karan and Irizarry, 2015).

UAS are aircraft and as such airworthiness will need to be demonstrated, and they are also systems consisting of ground control stations, communication links, and launch and retrieval systems in addition to the aircraft itself (Dalamagkidis, 2015). In construction and infrastructure environments, significant advantages of employing UASs are effective monitoring of the overall project logistics including site condition, traffic, equipment, or vehicle operations, and hard to reach areas on the jobsite (Kim, Irizarry and Costa, 2016). Visual assets collected with the UAS have been considered very useful for monitoring and inspection tasks on the construction and infrastructure sites, such as progress monitoring (Golparvar-Fard et al., 2009; Freimuth and König, 2015), safety inspection (Irizarry, Gheisari and Walker, 2012), construction surveying (Siebert and Teizer, 2014), site condition monitoring (Perez, Zech and Donald, 2015), bridge inspection (Metni and Hamel, 2007; Gillins, Gillins and Parrish, 2016), or road condition inspection (Zhang, 2008; Hart and Gharaibeh, 2010). The potential of 3D engineered data has also been emphasized in the construction and infrastructure domains (Remondino et al., 2011; Solihin, Eastman and Lee, 2017). The 2D images collected by UAS are used to develop this 3D data, which requires computational image processing. Several commercial applications, such as Pix4D or Photoscan have been described to develop the 3D data. These applications allow users to generate three different types of data, such as point cloud, DEM or DSM, and orthomosaic photos based on the user's properties and commands. Many recent studies have been investigated the potential advantages of the 3D data uses, such as pavement condition inspection (Zhang, 2008; Dobson et al., 2013), bridge inspection (Jáuregui, Tian and Jiang, 2006) or 3D model reconstruction (Dai et al., 2013). According to the particular studies about 3D model reconstruction, the scanned or surveyed 2D data could be transformed into a highly detailed 3D data, and this could be processed to create an object-based 3D model in the BIM environment (Hichri et al., 2012).

Data collected from UAS have been used for generating the 3D model and developing BIM on the purpose of detecting construction progress (Vacanas et al., 2015). For example, the interaction between BIM and UAS has been studied for construction progress monitoring by comparing as-built data collected from UAS operation with as-planned data in BIM (Vacanas et al., 2015; Hamledari, 2017; Moeini et al., 2017). These researches have approached the integration of BIM and UAS as the one-directional data transmission from UAS to BIM. However, UAS will require the data such as geological construction site information (e.g., area boundaries and altitude) which is already generated in BIM as a building information container during the entire project lifecycle (Vanlande, Nicolle and Cruz, 2008; Vacanas et al., 2015). On the other hand, BIM-integrated UAS operation has been presented by re-representing building geometry with converting geo-located points for UAS operation (Freimuth and König, 2015). UAS flight simulation in the re-located BIM environment has also been implemented for automated inspections on construction site (Freimuth, Müller and König, 2017). However, highly structured geometry or mapping inside the BIM platform has been imposed a heavy burden to operate in the current computing capacity (Solihin et al., 2017). In this respect, the operation of UAS within BIM platform becomes hard to integrate two platforms because of heavy computing time and cost. Regarding UAS operation requires specific data in BIM, extraction of specific BIM data can realize seamless interoperable environment between BIM and UAS.

Since the UAS operation requires the flight parameter-related information based on the building details for reliable flight mission, and it is possible that the BIM model contains the information, data flow from BIM to UAS could be defined for completing interoperable data environment. In this respect, the data exchange framework should also be defined to broaden the integration of BIM and UAS applications through iterative data extraction whenever the data requirements are changed. It will contribute to facilitating collaborative construction environment with a better understating of the interoperable environment between BIM and UAS.

3. RESEARCH FRAMEWORK FOR UAS AND BIM INTEROPERATION

This section provides an overview of the framework for developing an interoperable environment of the BIM and UAS operation. The UAS operators are usually required to establish the flight goals and parameters to develop the flight mission plan (Nex and Remondino, 2014; Federman et al., 2017). To execute the developed research framework in this paper, the flight mission data should be identified. Table 1 shows all the information, including the goals, parameters and additional information to develop the UAS flight mission plan.

Table 1: Flight Mission Planning Data

Flight Mission	Data
Flight goals	Point of interests; Type of UAS platform (UAS selection to connect); and Type of visual assets to be collected
Flight parameters	Altitude (Maximum 400ft); Boundary (point of interests); Location of the structures; and Offset distance from the structure
Additional information required	Camera setting; UAS speed; and UAS takeoff and landing location

3.1. Phase 1: BIM Data Extraction

In this step, a BIM data extraction framework has been developed to extract data potentially required for UAS mission plan in Figure 1. Object-based parametric modeling enables to import and export data in BIM by providing machine-readable data (Eastman et al., 2011). In this respect, this research presents to use ODBC (Open Database Connectivity) to extract data from BIM. Regarding ODBC provides a database of building information before we sort specific data, we can have more flexibility when UAS requires further dataset in the database. The database will be connected to MATLAB as a data source. We can easily access specific objects and their attributes in the connected building database. Referring to flight mission planning data identified in the pre-processing step, the potential dataset for UAS flight mission planning was to being imported in MATLAB workspace. Since the objects are composed of rules and attributes, several attributes were already abstracted based on parametric rules. For example, wall components have a base and top constraints, as parametric rules, rather than level attributes. The base and top constraints are indicated as level id which is generated numeric data when BIM modeler create levels in the project file and is disclosed in the level object. Within level objects, the ids should be mapped into level elevation to input as altitude data for flight mission plan, as well as the level name to contain meaningful information.

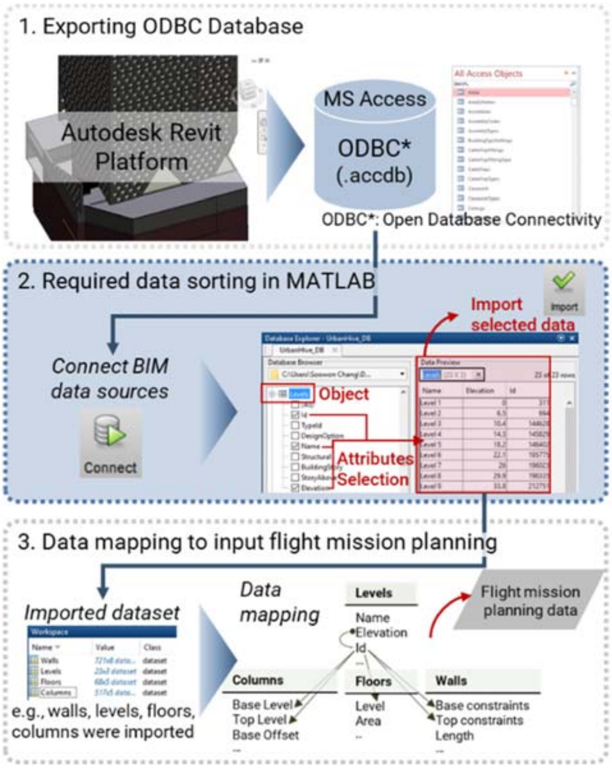

Fig. 1: BIM data extraction methodology framework

3.2. Phase 2: Flight Mission Plan Definition

In this step, the mapping data extracted from BIM will be plugged into the flight mission plan in Pix4D Capture, one of the UAS applications. In this study, the commercial software, Pix4D is employed to develop a flight mission plan and conduct the image processing. This software offers the users both desktop version (Pix4D Mapper) and mobile applications (Pix4D Capture) and can provide the ease of uses and simple workflow from developing the flight mission plan on the mobile application to the photogrammetry process on the Pix4D Mapper. Among data requirements for flight mission plan, we found out several data, such as types of drone or camera information are only available to be assigned in the Pix4D Capture application environment. On the other hand, the specific data extracted from BIM can be reused for flight mission plan data by exchanging data with shared meanings. In the preliminary research, we defined the exchangeable data extracted from BIM can be an area of interest, altitude, and units. The area of interest in Pix4D Capture consists of types of the mission plan, vertices of the mission boundary, centroid, start, and endpoints. Altitude can be inferred from the elevation of the target area. Project unit already assigned in BIM can be directly used as units of UAS operation. Table 2 illustrates the available data from BIM and the required data sets in Pix4D Capture environment. This paper presents the architecture for realizing the semantic interoperability of BIM data with flight mission plan shown in Figure 2.

Table 2: Preliminary flight mission plan definition

Data source	Mission data definition
Available data extracted from BIM	Area of Interest; Types of mission plan (polygon, grid, double grid, circular, free flight); Vertices of boundary; Centroid, Start and endpoints; Altitude of flight; and Units
Arbitrary data in UAS application	Type of UAS Platforms; Camera Setting; and GSD (automatically assigned along with altitude)

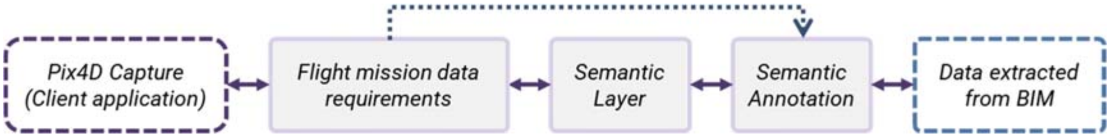

Fig. 2: Framework for semantic interoperability of BIM data with Flight mission plan

The framework is based on the existing semantic concepts in geomatics engineering (Bakillah et al., 2013). Data extracted from BIM will be defined as semantically homogeneous terminology required in Pix4D Capture in the semantic annotation step. In the semantic layer, more complex queries will be required to communicate client application (Pix4D Capture) and semantically defined data. In this research, we focused on presenting exchangeable data and potential data mapping between BIM and UAS operation. Therefore, we have investigated semantic mapping between BIM data and flight mission data in Figure 3. Based on the example of semantic mapping, the semantic annotation will be conducted to resolve semantic heterogeneities; then the homogeneous data will be transferred to the client application in the semantic layer.

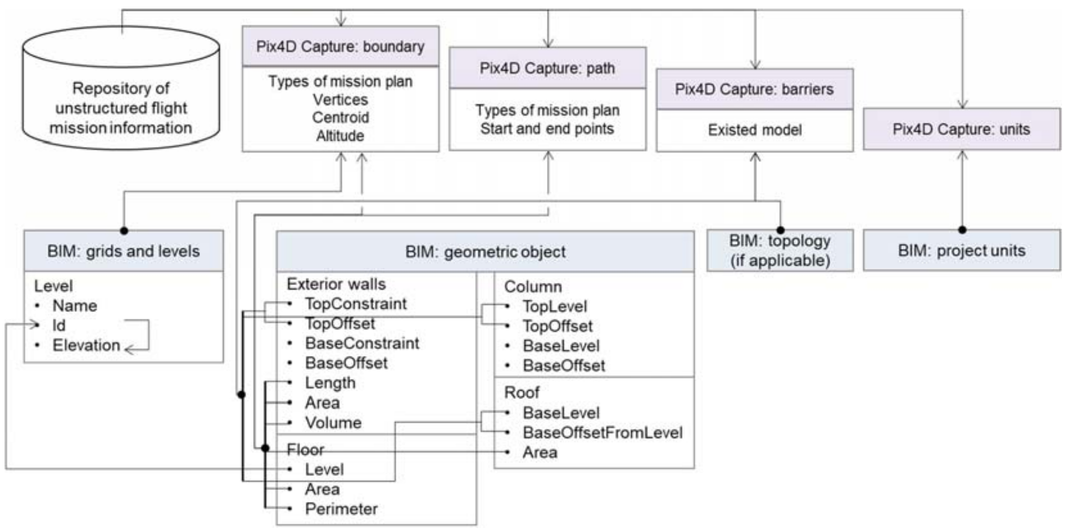

Fig. 3: Example of semantic mapping between BIM data and flight mission data

3.3. Phase 3: UAS Operation and 3D Data Processing

The main goal of this step is to capture the 2D image data during the operation, and the process the 3D data based on the collected 2D images and photogrammetry process. In this stage, a UAS platform will be deployed over the point of interests defined during the pre-flight stage and flight mission determine. Pix4D Capture has required the connection with the platform to be operated and the check the flight telemetry of the platform before starting the mission. The application will conduct the UAS takeoff check, and this allows the UAS to operate automatically over the defined area by following the defined mission. During the flight, the UAS will capture 2D images based on the image acquisition plan and camera setup. The images would have enough common characteristic points in each image data set as well as between the dataset, to organize and overlap each image during the 3D photogrammetry process. The photogrammetry has three main steps: (1) image organization and setup coordination system; (2) image mesh and point cloud; and (3) 3D model texture and DSM (Kim, Irizarry, and Bastos Costa, 2016). The generated point cloud data could be imported to the BIM application, to convert into an object-based model called as an as-is model describing the current condition of the area captured by the UAS during its operation.

3.4. Phase 4: Update As-Is Model

This step currently requires the manual process to convert from the point cloud data to the object-based 3D model in the BIM environment. This process includes to create the native geometry on the 3D model and to place all the building components, such as walls, columns, and even windows (Hichri et al., 2012). Therefore, the data-rich geometry model can recognize all the architectural elements

3.5. Overview: Framework for Interoperable Environment of UAS and BIM

The scope of this paper is to provide the research framework that the authors have been investigating to develop the interoperable environment of the UAS and BIM within construction and infrastructure environments. Figure 4 illustrates the proposed framework for the entire research. As-planned BIM model, which is the initially designed model in the early construction step, will be given to defining the flight parameters could be extracted from BIM. This data will be transmitted to the commercial flight mission planning systems, and it will be coordinated with the technical information, such as camera setting or UAS connection to determine the flight mission plan. When the mission is delivered to the UAS platform, it starts to collect the 2D images during the flight operation. Since the UAS is equipped with the Global Positioning System (GPS) and other telemetry sensors, the captured 2D images are geo-referenced and each image set has the common key-points will be overlapped on image organization during the image-processing step (Photogrammetry). The main product of this process is the point cloud project data (.rcp format), and it can be converted raw point cloud data as a reference model in the BIM application. An as-is model will be processed through the image and pattern recognition on all objects, such as walls, columns, or windows. The as-is model will be regularly updated based on the periodic schedule of UAS operation, which means that it can support the users with updating current work progress. The BIM environment can also store each flight parameter data as often as each flight mission plan is developed.

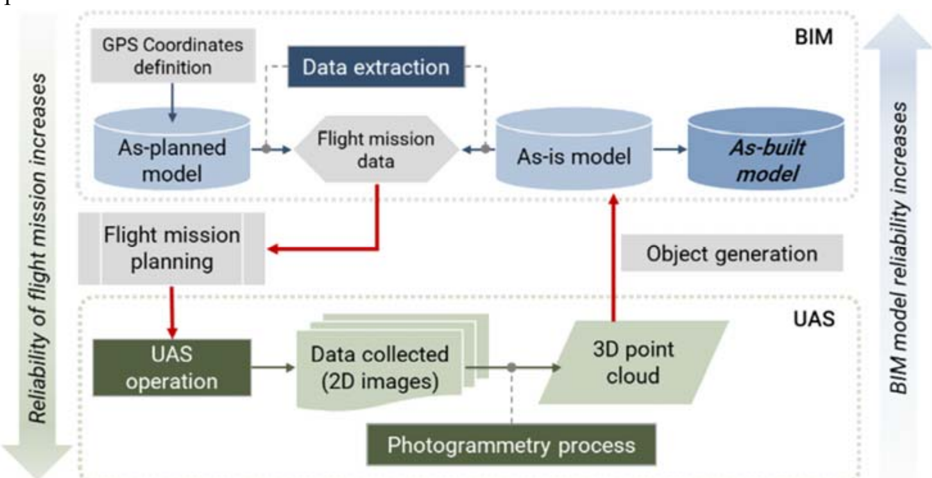

Fig. 4: Proposed framework for the interoperable environment of UAS and BIM

4. DISCUSSION

This study describes the data interoperability between the UAS operation and the BIM environment. The main challenge of the current flight mission plan requires several manual flights to obtain flight parameters, such as altitude or maximum distance on the job site since the current software cannot provide the information about the work progress or accurate geological data required to determine the flight mission. BIM environments could describe all required geological parameters since all components consist of geometry information. BIM data mapping into UAS flight mission application (Pix4D Capture) enables not to have absolute coordinates mapping in a BIM environment because UAS application provides user-interface to utilize UAS in user-oriented perspective. An as-planned model can give the users an opportunity to extract the initial flight parameter information needed to define the mission plan.

This paper presents the framework summarizing which parameters could be extracted from the BIM environment, which data should be defined in the current applications, and how the UAS can operate based on the defined flight mission as well as provide the visual data to develop an as-is model. This system will be able to offer UAS practitioners in the construction and infrastructure more reliable flight mission development system. BIM can store the parameter data could be easily updated and extracted for next flights. This makes the operators skip the additional manual flights. Another potential of this study is to improve the safety issues during the UAS operations in the construction environments. The most important issue of the UAS operations has the safety of project-related resources, human resources involved in the project, as well as the public or neighbors. Since the flight missions developed based on this system could rely on the recent work progress, the UAS operations could avoid the significant accidents, for example, head-on collision with the structures, and the UAS should be dropped over the workers, pedestrian, or even private properties, consequently loss of lives.

One of the main challenges to be considered is the regulatory environment, called as PART 107 established by the Federal Aviation Administration (FAA). According to this regulation, the UAS platform cannot fly over the 400ft and must be maintained within visual line of sight (VLOS) of the UAS operators during the flight operation. Therefore, the maximum range of the UAS flight mission should be limited. Another limitation of this study is the error of the ground positioning system (GPS) equipped with the UAS. Since the off-the-shelf UAS platform will be used during the field-testing, the error of GPS is out of the control of the authors. To avoid the accident of the platform, the flight parameters regarding offsets from the structure, distance, or altitude will be defined within a reliable and safe range. Also, the ground control points will be used to increase the accuracy of the 3D model during the field-testing. Based on the developed framework in this paper, the authors will develop the BIM data extraction application in MATLAB code, and the data will be transformed into programming language through the compiler library in MATLAB. Further investigation of Pix4D Capture’s application programming language (API) is required for the appropriate transformation with realizing semantic rules to develop semantic annotation and semantic layer.

5. CONCLUSION

In this paper, a framework for semantic interoperability of BIM and UAS was presented. This work is part of an ongoing research effort to achieve the seamless practical interoperable environment between BIM and UAS operation in a construction environment. The main contribution of this work is presenting an interoperable semantic environment between BIM and UAS for maximizing time- and cost- efficiency on jobsite with minimizing data confusion. A semantic data mapping in an intermediate platform will enable BIM and UAS interoperation without burdening each application. Furthermore, UAS operator, BIM modeler, and project engineer can collaborate with clear agreements of role and responsibility for UAS operation by defining available BIM data and flight mission information which cannot be structured for inputting as a dataset. While the development process should be conducted for implementing the framework of BIM and UAS operation, the proposed framework will present reinforcing feedback of increasing reliability for UAS operation and as-built BIM model generation. To verify the framework’s validity, a field test is planned in the future. Based on the developing process and field testing, the research framework will be developed to achieve practical interoperation of BIM and UAS.

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BIM Logic Mechanism and Its Function

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ABSTRACT: *Construction Engineering Semiotics, the first monograph on the basic theory of Building Information Model (BIM), is a new monograph written by Professor Ren aiming at establishing the basic theory of BIM software development. The BIM pre-life cycle subsystem and mid-life cycle subsystem are the two core subsystems describing the whole construction project process, and the BIM pre-graphic data system and the management planning data system are the corresponding data of the two core subsystems, so they are collectively referred to as BIM data. The application of BIM pre-graphic data can reproduce the simulation graphics of the construction project called BIM pre-graphics, and the application management planning data can reproduce the BIM management plan of the construction project. The former develops in an orderly manner according to the hierarchical structure of subsystems and sub-subsystems, describing the state in which the construction project is designed to run in an orderly manner, called BIM pre-graphic logic; the latter describes in real time the orderly running state of any node built by the construction project, called BIM Planning logic. China has not yet been able to develop BIM core modeling software. In the process of learning and studying foreign BIM core modeling software (such as Dassault Systèmes in France), we found that Dassault Systèmes only had BIM pre-graphic logic and no BIM planning logic which is a theoretical defect. Thus, the theory of solving this theoretical defect - BIM logic mechanism came into place, and is discussed and illustrated in this paper. This study can potentially benefit the development of BIM core modeling software in the future.*

KEYWORDS: *BIM logic; BIM logic mechanism; BIM engineering project management; BIM engineering project management system software; BIM digital construction; property BIM system software*

1. BIM LOGIC MECHANISM

"Construction Engineering Semiotics - Basic Theory of BIM Digital Engineering and BIM Technology" (construction engineering semiotics) (Ren, 2016) is a new monograph written by Professor Ren on the basis of his monograph "Engineering Coordination Technology". There are two articles in the construction engineering semiotics. The BIM design theory and the BIM software development concept are the second articles. There are eight chapters in construction engineering semiotics, and five chapters in the second articles: Chapter 4 BIM software development concept; Chapter 5 BIM construction project design software; Chapter 6 BIM construction management software; Chapter 7 BIM enterprise information platform; and Chapter 8 BIM property project operations software. BIM enterprise information platform is essentially a comprehensive software platform which is a concept of BIM software set.The establishment of the basic theory of BIM software development is the main task of the second article, and the BIM logic mechanism discussed in this paper is its core theory.

1.1. The Connotation of BIM Logic

1.1.1 BIM Pre-Graphics and BIM Management Plan

BIM pre-life cycle subsystem and BIM mid-life cycle subsystem are two core subsystems that describe BIM project management. The BIM pre-graphic data and management planning data are the corresponding data of the two core subsystems, so they are collectively referred to as BIM data. The BIM pre-graphic data can be used to reproduce the virtual graphics of the construction project, called the BIM pre-graphics. The BIM management planning data can describe the real-time running status of any node of the construction project, called the BIM management plan. If the correspondence relationship between the BIM pre-graphics and the BIM management plan together with its data is established, the BIM pre-graphics, BIM management plan and digitization are realized in a construction project.

1.1.2 Definition of BIM Logic and its Connotation

The BIM pre-data and BIM management planning data can be used to reproduce BIM pre-graphics and describe the BIM management plan in real time, revealing the structure of the construction project itself in the BIM pre-life cycle subsystem and BIM mid-life cycle subsystem, and describing the orderly operation status of construction project, called BIM logic which can be divided into BIM pre-graphic logic and BIM management planning logic. BIM logic also describes and reveals the characteristics of the same construction project from these two different perspectives: (1) BIM pre-graphic logic reveals the hierarchical structure between the BIM pre-life cycle subsystem and sub-subsystems in a graphical logic way, and reveals also the internal relationship between BIM pre-graphics and BIM pre-graphic data; (2) BIM management planning logic reveals the internal relationship among BIM mid-life cycle subsystem elements by way of a planned logic, revealing its fractal characteristics and hierarchical structure characteristics as well as the internal relationship between BIM management plan and BIM management planning data. BIM logic reveals the internal relationship between the BIM pre-life cycle subsystem and BIM mid-life cycle subsystem. There is compatibility between BIM pre-graphic logic and BIM management planning logic. The expression of BIM management planning logic cannot be realized by using BIM construction graphics—that is, the BIM pre-graphic logic cannot replace the BIM management planning logic. BIM logic is the way of understanding of the objective world in the struggle for survival. The BIM logic is implemented in a construction project on the condition that the BIM pre-graphic logic and BIM planning logic are implemented.

1.2. The Connotation of BIM Logic Mechanism

1.2.1 BIM Management Planning Software and BIM Core Modeling Software

1.2.1.1 BIM Management Planning Software

Single code plan and dual code plan (or traditional network plans) have reverse computing program with defects and errors in system structure incompatibility. Structural Symbolic Network Plan (or BANT Plan) is a new network planning method designed by researcher Ren Shixian, especially for the defects and errors in traditional network plans. No reverse computing program is the distinct characteristic of the BANT Plan mathematical model (BANT algorithm). Three projects under the development of the BANT Plan and its software were funded by the National Natural Science Foundation of China (NSFC), and the technical software of BANT Plan has been successfully developed. The monograph "Engineering overall Planning Technology", which is the comprehensive achievement of the project, has been published and funded by NSFC (Zhou, 2003). It should be noted that "Engineering Overall Planning Technology" is an illustrated monograph, and its planning curves are drawn using BANT Plan technology software (Liu, 2015). The introduction of the BANT Plan into BIM is indicated as the BIM-BANT Plan, supplemented by a 3D plan called the BIM Management Plan (BIM Plan) (see Figure 1). The BIM management Plan and the BIM Plan are the same below.

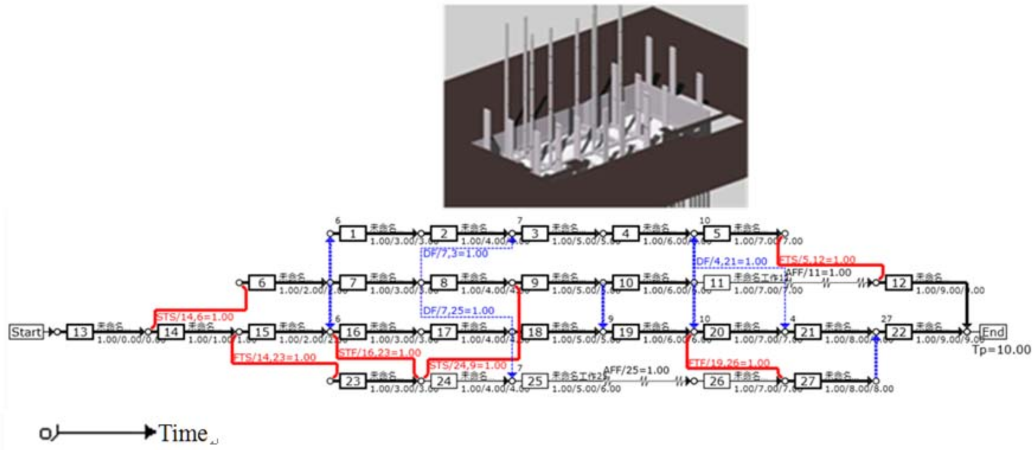

Figure 1 BIM qualitative lap management plan for a construction project (Real time operating state diagram at BIM node 9). Furthermore, there are two main key points on the development of BANT. First, the BANT qualitative plan (or equal rights plan) solves the logical relationship among elements, and the time units (year, month, week, and day) are set in the BANT quantitative plan (time scale plan). Second, due to the format, as expressed by way of the BIM qualitative management plan in Figure 1, the BIM time-scale plan in the figure can be seen by clicking the "time scale plan" button of this software. Moreover, if a user wants to know the real time running status of the construction project at any time, he/she just needs to click on the BIM node at any time on the software to see the BIM management plan as shown in Figure 1.

1.2.1.2 BIM Core Modeling Software

In the design phase of the construction project (or the BIM pre-life cycle), the application of BIM pre-graphic data can reproduce the virtual graphics of the construction project, called BIM graphics simulation which is a basic characteristic of the BIM. The software developed by applying BIM graphic simulation design theory is called BIM graphic simulation design software which is the BIM core modeling software, including a series of software such as architectural design, architectural structure design, construction equipment and pipeline.

The various types of software brought about in the BIM pre-life cycle are called BIM construction project design software, a software package for realizing the comprehensive design of the construction project and establishing the BIM database. BIM core modeling software is the core software of BIM construction project design software. Implementing the BIM design model of the construction project and establishing the BIM database are the main objectives of the BIM core modeling software. There is compatibility between BIM graphical simulation design software and BIM management planning software. The objective of developing BIM management planning software is to generate the BIM management plan by transfer of the related data of the BIM database; among them, the automatic generation of 3D plan function development is of great significance, and its successful development not only means the successful establishment of the construction project database, which is the BIM database but also verifies the compatibility of the two.

1.2.2 BIM-WBS software and BIM database

1.2.2.1 BIM-WBS Software

The BANT Plan has a hierarchy called a BANT nested structure. The BANT nested structure is introduced into BIM and is called the BIM-BANT nested structure, or the BIM nested structure. The BIM nested structure is a model for the work breakdown structure of the construction project, called the BIM-BANT-WBS work breakdown structure, or the BIM-WBS structure, which is the hierarchical structure of a construction project. The software developed according to the BIM-WBS work breakdown structure concept has the function of decomposing the construction project into a BIM nested structure and encoding the BIM-WBS structure, called BIM-WBS software. The BIM-WBS software provides a BIM database with a BIM work breakdown structure.

1.2.2.2 BIM Database

The BIM core modeling software will generate huge data in the design process of the construction project. The way to organize, store and manage these data is called BIM database. BIM graphical simulation design is the process of establishing BIM database. The realization of the identity between BIM pre-graphic model and BIM pre-data model is the most important way to establish BIM database. Construction project BIM has only one identity. Therefore, the BIM database is unique: the engineering data of the same component element in the BIM database can be shared by each related work type, that is to say, the engineering data of the element is shared. The BIM database consists of two parts: (1) the result of BIM-WBS structure decomposition of the construction project, which is called the nested hierarchical structure of the BIM database, or BIM database structure; and (2) the coding result of the BIM database structure, which is called the nested hierarchical structure coding of the BIM database, or BIM database structure coding. The design of the BIM database should consider the internal relationship between the BIM pre-life cycle and BIM mid-life cycle subsystems and realize its compatibility and connecting function, which is called the hub function of the BIM database.

1.2.3 Definition of BIM Logic Mechanism and its Connotation

The BIM pre-graphical logic reflects the spatial state of the construction project. The BIM planning logic describes the time course of the construction project operation. There is internal relationship between the two which exist independently in their respective ways and cannot mutually be replaced. The BIM database is the hub of its connection. There is compatibility between the BIM pre-graphic data and the BIM management planning data. In addition, there is synergy between the BIM pre-graphics and the BIM plan, which is called the logic mechanism of the BIM project management system, or BIM logic mechanism.

BIM design software and BIM construction management software of construction project are collectively named as the BIM engineering project management system software. BIM graphic simulation design software is the core software of BIM engineering project design software. BIM project management software is the core software of BIM construction management software, and BIM management planning software is the core of BIM project management software. There is an internal relationship between BIM construction project design software and BIM construction management software and compatibility between the two. The BIM database is the hub of its connection. According to the BIM logic mechanism, the development of BIM software should solve the compatibility between BIM graphics simulation design software and BIM management planning software. BIM database is a bridge to solve the compatibility between the two.

2. FUNCTION OF THE BIM LOGIC MECHANISM IN BIM SOFTWARE DEVELOPMENT SYSTEM

2.1 BIM Engineering Project Management System Software

2.1.1 BIM Engineering Project Management

BIM utilizes the waste of traditional data resources to produce BIM technology, which is a wonderful work in the history of human resources management and technology development and belongs to the category of engineering management. The introduction of engineering project management into BIM is called BIM engineering project management which is the management theory and method of BIM life cycle of a construction project. It is the way the project management enterprises implement the life cycle or selected stages of management and service of construction projects. This is the product of the integration of human resources management and methods. BIM technology is the big data of construction project, which marks the birth of a new model of engineering project management, namely BIM engineering project management, a theoretical system based on BIM.

2.1.2 Definition of BIM Engineering Project Management System Software

BIM design software and BIM construction management software of construction project are both about the concept of software packages which are all generated in the BIM pre-life cycle and BIM mid-life cycle subsystems, collectively referred to as BIM engineering project management system software, or BIM software. The BIM software should link the pre-life cycle and mid-life cycle of the construction project through the BIM database, standardize the exchange of various information with the unified data source, and coordinate the compatibility of the information flow to ensure the smooth flow of the system information.

2.2 BIM Property Project Operation Software

Investors are the owners in the design phase and construction phase of a construction project called the investment project owners. When the complete data of a construction project is handed over to the relevant government departments and successfully entered the market, the mission of the investment project owner is completed, and the manager of the construction project has a new connotation, called the construction project property operation owner, or the operation owner. When the owner of the construction project hands over the complete data of the construction project to the relevant functional government department, it indicates the end of the construction design phase and the construction phase of the construction project; and once the complete data of the construction project is handed over to the property operation department, the investment project owner is changed to the operation owner. These market function signs of construction projects appear. At this point, the construction project is truly entering the operational phase of the construction project, that is, the operation phase of the property project and the change of the construction project to the property project is its distinctive characteristic. BIM engineering project management does not cover the application phase of the property project. Based on this, the construction engineering semiotics established the management theory of the property operation stage and is called the BIM operation management theory of the construction project, referred to as the BIM operation management theory.

The software developed using BIM operation management theory is called BIM property project operation software. The data generated by the BIM property project operating software is called BIM property operation data, which reflects the BIM property project's own characteristics, social functional characteristics and cultural functional characteristics. The BIM property project operation software is generated during the operation phase of the property project belonging to the post-life cycle subsystem software. Although BIM engineering project management only plays its role in the design and construction phase, and only BIM digital construction can play a role in the property operation phase, it still falls within the scope of BIM engineering project management. BIM property project operation software is service management software. The BIM property project operating software is a specific type of property BIM system software.

2.3 Development Requirements for BIM Core Modeling Software

BIM-WBS method brings about BIM database development. Data generated in BIM graphic simulation design should be automatically input into the BIM database. BIM project management software must not only be able to read the relevant data of the construction project from the BIM database, but also can directly extract the BIM-WBS coding structure of the construction project, which is a harmonious overall design, called BIM engineering project management system software development system based on BIM logic mechanism, referred to as BIM software development system. The development of BIM core modeling software should follow the BIM software development system and link the design and construction management of the construction project. This is the core content of the BIM software development system.

3. FUNCTION OF THE BIM LOGIC MECHANISM IN BIM SOFTWARE

IDENTIFICATION CRITERIA

3.1 Property BIM System Software

3.1.1 BIM Digital Construction

The simulation-based digitization method is the product of the third industrial revolution, called graphic simulation digital engineering technology, referred to as simulation digital engineering. Obviously, digital engineering is a digitization method for graphical simulation. By introducing the concept of digital engineering into the BIM, and establishing a corresponding relationship between the construction project graphic model and its data model, the BIM pre-graphic model of the construction project is thus obtained, and its data can be used to reproduce the virtual graphics of the construction project, called BIM simulation digital engineering technology of construction project, referred to as BIM digital engineering. BIM digital engineering transforms complex, variable, discrete and unstructured information of construction projects into measurable data and data sets. This is the new digitization method of the fourth industrial revolution.

3.1.2 Definition of property BIM system software

BIM digital construction is exposed to the fields of digital architecture, 3D printing, digital manufacturing, government data, smart city and data industry relying not on BIM engineering project management theory but on BIM digital construction theory. The software developed with BIM digital construction theory is called BIM digital construction system software. This is an open concept which covers software developed in various fields using BIM digital construction theory, such as smart site software, smart city software, robot software and 3D printing software, and are BIM digital construction system software. In order to distinguish it from the BIM engineering project management system software, the construction engineering semiotics is called the BIM digital construction system software, or the property BIM system software.

3.2 Comparison of BIM Software and Property BIM System Software

There is a fundamental difference between BIM software and property BIM system software (see Table 1). It can be seen from Table 1 that BIM engineering project management and BIM digital engineering belong to the theoretical system based on BIM, which are all about the concept of BIM life cycle. BIM graphic simulation design software and BIM management planning software are the core software of BIM software which is developed following BIM software development system, and BIM digital construction is based on the theoretical system of digital design, a non-BIM life cycle concept. The property BIM system software has no core software, so it does not have BIM Software development system. Because of the BIM software development system is derived from the BIM logic mechanism, the substantial difference between the BIM software and the property BIM system software depends on whether the BIM logic mechanism exists or not. Therefore, the BIM logic mechanism is the identification standard for BIM software and property BIM system software.

Table 1. Comparison table of BIM software and property BIM system software

	Compare Content	BIM Project Management System Software	Property BIM System Software
1	Support theory	BIM project management theory	BIM digital construction theory
2	Relying on the owner	investment project owner	property project owner
3	Core software	BIM graphics simulation design software and BIM management Planning software is BIM project management The core software of the system software	The software developed in various fields using BIM digital construction theory belongs to the property BIM system software, so there is no core software
4	Whether to follow the BIM software development system	BIM graphic simulation design software and development of BIM Planning management software follows the BIM software development standard	BIM software development standard does not exist. In the property BIM system software
5	Is there a configuration Quality check Software	BIM graphics simulation design software and BIM management plan software are configured corresponding quality verification software	Property BIM system software does not involve configuration quality verification software problem
6	Model type and its physical essence	BIM project management system software belongs to BIM project management model, this is about the concept of BIM life cycle	BIM property system software belongs to non-BIM project management model, this is a non-BIM life cycle concept
7	Object-Oriented	Object-Oriented for Construction Projects	Object-Oriented for fields in Smart Buildings, Smart Cities, Government Data, Digital Earth, 3D Printing, Robotics, and Data Industries

4. SUMMARY

Only BIM pre-graphic logic but without BIM management planning logic are the theoretical defects of BIM core modeling software at home and abroad. Therefore, the application of BIM logic mechanism is an important discovery and innovation of construction engineering semiotics. The BIM logic mechanism provides a theoretical basis for the identification and division of the two major software types of BIM engineering project management system software and property BIM system software. The BIM logic mechanism has derived the theory of BIM software development system, which is of great theoretical and practical significance for the development of BIM software. Studying the history of emerging and development of BIM, based on the current international definitions and referring to relevant literature and materials, the author put forward his definition of BIM as “BIM is the information integration model of building projects, through the graphic simulation of building projects in obtaining its corresponding data (digits and set of digits), and using such data to reproduce the real graphics of building projects is its distinctive feature. It should achieve the graphics and digitalization of building projects, provide all parties concerned with a comprehensive source of effective data which can be used to implement the construction and operation of building projects.” (Ren 2011).

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BIM Implementation: Articulating the Hurdles in Developing Countries

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ABSTRACT: *BIM has become the leading topic of discussion in the construction industry globally. BIM provides limitless opportunities revolving around efficiency; thus, researchers have subjected it to continuous research in order to harness all inherent benefits for the construction process and product. However, the widening gap in BIM adoption between developing and industrialized countries is alarming. While industrialized nations are researching a higher level of BIM adoption and the exploration of BIM to access boundaries yet unknown, developing countries are battling with creating awareness for 2D and 3D BIM category tools. Hence this study to articulate the hurdles to successful BIM implementation in developing countries. This was achieved through an exploratory research design. Semi-structured interviews were conducted. The interview was transcripted and analyzed using Atlas.ti 8. The study established the hurdles to BIM execution as under five themes: policy, culture, education, transparency, and infrastructure. Specific recommendations for crossing these hurdles were also provided in the paper. Nevertheless, achieving full BIM adoption in developing countries fundamentally requires stakeholder's synergy, the transparency that assures shared data integrity, developing dynamic capability, and a complete shift from the traditional model of project administration.*

KEYWORDS: *BIM adoption, BIM barriers, BIM competitive advantage, BIM hurdles, BIM infrastructure, BIM implementation. construction industry culture.*

1. INTRODUCTION

BIM is an innovation that has been accepted by the construction industry to disrupt its process and product delivery procedure. Thus it has taken the front line in the discussion and race for adoption by different countries due to its inherent benefits to the construction instruction. Jung and Lee, (2015) carried out a study to establish a BIM adoption status across the six continents. The study gave a comparison and also pitched how each continent was fairing against the global performance. It also classified the innovation adoption phase of each continent as regards BIM. Some other empirical studies have been carried out to determine the BIM adoption level in countries. For instance, Santos *et al.*, (2015) carried out a study to establish BIM maturity in Brazil, where they established the tools and category of adoption in the industry. These and several other studies have been embarked upon to establish the rate of BIM adoption. These studies show the disparity in BIM adoption rate, level of adoption of each country and the disparity between industrialized countries and developing countries to be wide. This study is therefore embarked upon to articulate the hurdles preventing the BIM implementation in developing countries. However, the study used Nigeria as a case study.

2. LITERATURE REVIEW

The disparity in the BIM implementation in the construction industry is considered bad for the construction industry. This is because it will be a clog in the wheel of globalization in the construction industry. Thus developing countries will be victims instead of beneficiaries and active participants in globalization (Ofori, 2001) if this trend of disparity continues without a check. Table 1 below shows how the Middle East and Africa performs against the rest of the world in terms of frequency of BIM services uses. A glance at this table gives a satisfactory impression for the middle east and Africa. However, the conclusion of the study classified the continents to be at a “beginner phase”(Jung and Lee, 2015).

Table 1: Use frequency of BIM services used in each continent (Jung and Lee, 2015).

	Overall	Middle East and Africa
3D coordination	85.0%	91.7%
Cost estimation	75.0%	58.3%
Existing condition modeling	74.3%	66.7%
Design authoring	63.4%	83.3%
Structural analysis	60.0%	50.0%
Maintenance scheduling	30.1%	16.7%
Building system analysis	33.4%	25.0%

This depicts that despite the encouraging figures in table 1, there are different levels of adoption. Table 2 shows the different categories of BIM

Table 2: Category BIM classification (Santos *et al.*, 2015)

Data Category	Information	Characteristics
CAT-0	2D	Bi-dimensional in- formation
CAT-1	3D	Tri-dimensional information
CAT-2	BIM	BIM for architectural Modeling
CAT-3	i-BIM	Structural Analysis
CAT-4	i-BIM	Building Systems / HVAC
CAT-5	i-BIM	Thermal and acoustic analysis
CAT-6	i-BIM	Infrastructure Projects
CAT-7	i-BIM	BIM Integration / Interoperability

It is evident from table 2 that there exist different categories of BIM, it is thus imperative for studies on BIM adoption to specify the extent and level. Also, from the table, it is evident that BIM begins from CAT-2. Thus CAT-0 and CAT-1 can be considered as preparatory, awareness and prerequisite phases necessary for the adoption of BIM. For instance an exploratory study by Hamma-Adama, Kouider and Salman, (2018), respondents exhibited a low awareness level and the study established that the few using BIM tools are 2D and 3D levels. This finding corroborates Fadason, Danladi and Akut, (2018) finding where it was established that the most used software in the Nigerian construction industry are 2D and 3D software. However, it is worthy of note that this adoption is majorly by Architects (Alufohai, 2012). Undoubtedly, given the potential inherent in BIM for the construction industry, many researchers have wondered why adoption has become a problem. This is evident in the different level of adoption among countries, it shows that countries are experiencing different levels of hurdles in the adoption of BIM. Table 3 gives barriers from previous literature. These studies span from 2014- 2018; thus, these studies have been studying the barrier in these years yet little or nothing has changed in the developing countries. Thus, this study seeks to build upon the previous studies but through an exploratory approach. This was adopted to get a better understanding of the problems.

Table 3: Barriers to BIM adoption in the Nigerian Construction Industry (NCI) from literature

Author	Findings
Ozorhon and Karahan, (2016)	-standard platforms for integration and communication - cost of development - education and training - standardization (product and process) - clear definition and understanding of users' requirement
Ibem *et al.*, (2018)	high level of awareness of BIM among architects in Lagos (common BIM software packages used are Autodesk Revit Architecture, AUTOCAD, and Google Sketchup.)
Kori and Kiviniemi, (2015)	most of the medium and larger-scale firms are significantly catching up toward the BIM practice, but the small-scale firms are having setbacks especially in the aspect of process and policy adherence. However, among all the groups, the level of technological workforce toward BIM and digital technology at large was found appreciable.
Olapade and Ekemode, (2018)	low level of awareness low-level adoption of BIM for FM
Hamma-Adama, Kouider and Salman, (2018)	key players are generally not familiar with the term "Building Information Modelling" or "BIM" although mostly aware of some of its tools (i.e. AutoCAD, Revit, etc.). low level of use BIM tools no legislative provision on BIM adopting or regulation. Lack of experts on BIM
Ugochukwu, Akabogu and Okolie, (2015)	Poor knowledge of BIM application among professionals Use of BIM in projects is non-existent lack of BIM awareness
Ryal-Net and Kaduma, (2015)	low level of BIM knowledge low level of awareness low level of utilization amongst stakeholders
Ezeokoli, Okoye and Nkeleme, (2016)	Structure/culture of the industry Level of Knowledge and Awareness index Availability of the appropriate Technology and Infrastructure Individual/Personal Disposition
Onungwa and Uduma-Olugu, (2017)	lack of infrastructure lack of skilled workers lack of awareness lack of support from leadership in the offices and lack of belief in the usefulness of the software.
Amuda-Yusuf *et al.*, (2017)	clients low level of awareness lack of funding poor power supply legal uncertainty lack of transparency.
Fadason, Danladi and Akut, (2018)	Lack of BIM education Lack of Information on BIM Lack of Investment in BIM Technology Lack of Government Support through legislation Lack of Standards to Guide Implementation Lack of sufficient ICT Infrastructure
Abubakar *et al.*, (2014)	social and habitual resistance to change' legal and contractual constraints' high cost of integrated software' Lack of enabling environment (policies and legislations of government towards the adoption) lack of trained professionals
Usman and Said, (2014)	culture policy cost

3. RESEARCH METHOD

The aim of this paper is to articulate the different hurdles to the adoption of BIM in the Nigerian construction industry and extension developing countries. This was achieved through an exploratory design. The data was collected through qualitative semi-structured interviews conducted on 6 practicings, construction industry professionals. The interviews were conducted on respondents individually and the validity was through logic. This method was chosen to get a better understanding of the hurdles (Kumar, 2011). Invitations were sent out to respondents however only six (6) respondents responded positively and they were interviewed. A total of 20 respondents were contacted but they indicated that they were operating a tight schedule and as such could not honor the interview invitation. The six that were interviewed are construction professionals, thus the responses are considered to be first hand, broad and with a lot of depth as it is based on experience. These professionals are involved in projects worth 100million naira approximately on average and work in the top construction firms in Nigeria.

Unlike a quantitative study, qualitative studies do not thrive on a large sample size. According to Kumar, (2011) "the numbers of people you are going to contact depend upon the attainment of the data saturation point during the data collection process…which can provide you, as far as possible, with the detailed, accurate and complete information that you are looking for". The most major factor for selecting respondents is their depth of experience of the problem being studied. The qualitative study approach was adopted to provide a deeper understanding based on the individual experience of the professionals (Castleberry and Nolen, 2018). All respondents are all working with consulting firms. This approach was chosen because the contractors are dependent on the software used by the consultants (Hamma-Adama, Kouider and Salman, 2018). Thus, the consultants drive the BIM adoption level in a project team. Consequently, it is the belief of this study that they are better positioned to be interviewed for the required information. Data analysis was achieved using Atlas.ti 8 software to create the knowledge network in Fig. 1 from the response gathered. ATLAS.ti is employed in the qualitative analysis of large bodies of textual, graphical, audio and video data. Thus, it is qualified to be used for this study where qualitative data was employed. The network shows the different quotations taken from the interview transcription, from these themes were generated to get a better definition of the hurdles under categories.

4. STUDY FINDINGS

The findings of this study were achieved through interviews. Figure 1shows the barriers to BIM adoption from respondents' statements. This was achieved with Atlas.ti 8. To allow for better discussion, these responses in figure 1 are categorized into the following themes:

- **Culture** includes rigidity to learning, isolated adoption efforts, lack of synergy, holding on to traditional contract method, lack of patience by clients, and client project funding approach
- **Expertise/Education** include disparity of BIM knowledge, unavailability of BIM information in the industry, the inclusion of BIM in the education system, lack of BIM experts among others.
- **Infrastructure** includes lack of infrastructure lack of training and tools, among others
- **Policy** includes government cluelessness, lack of interest by professional bodies, inadequate modelling system among professionals, among others
- **Transparency** includes lack of synergy, inadequate information sharing among professionals, unhealthy rivalry /competition among professionals.

4.1 Infrastructure

The needed infrastructure supporting BIM implementation is not readily available. These infrastructures include electricity, internet service availability, availability of favorable environment, among others. Previous studies identified electricity as a major barrier to adoption (Amuda-Yusuf *et al.*, 2017). However, the infrastructure needed is not limited to this. According to a report on digitization maturity in Africa by Siemens, (2017), ICT infrastructure is measured by two variables – access and use; and affordability. Presently, access and affordability to BIM infrastructure is non-existence. Thus, stakeholders are faced with the challenge to provide infrastructure. Sadly, they provide and

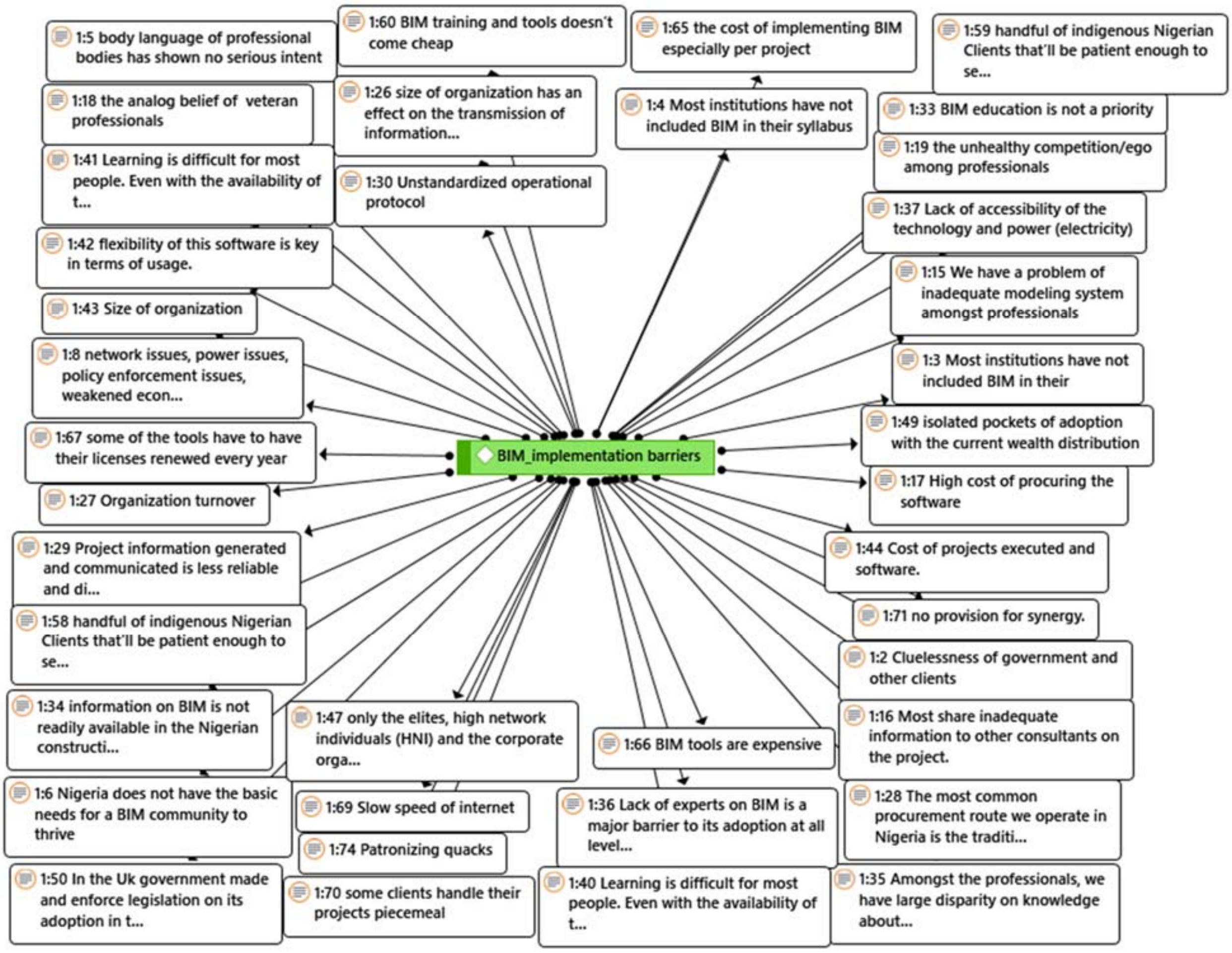

Fig. 1: Barriers to BIM adoption from interviews

maintain these infrastructures necessary for the uptake entirely. Moreover, Nigeria ranks low on the affordability of ICT infrastructure (Siemens, 2017). The absence of infrastructure and the necessity for its provision makes the cost of adoption to be high in terms of infrastructure and the purchase of the software. Cost of software purchase identified in this study corroborates the findings of (Usman and Said, 2014), this was identified as cost of integrated software by (Abubakar *et al.*, 2014), it is however identified in this study as the cost of periodic renewal of software license. The ability of organizations to overcome this challenge is dependent on their size and turnover. For the industry to experience a speedy and smooth adoption, the government needs to provide these needed infrastructures. This reduces the cost of initial implementation by firms and thus reduces the cost impact on construction industry products in the short and long run. Also, the industry can adopt "BIM fund" as adopted in Singapore (BCA, 2015). This will assist stakeholders to achieve BIM capability by offsetting the cost incurred in training, consulting, software or hardware.

4.2. Policy and standards

These work in synergy to establish and enforce requirements that guide a decision to achieve an outcome. A government-driven BIM adoption has been established to be effective, the United Kingdom is a good example. A survey to establish the BIM adoption globally using the Macro maturity components model was performed in 21 countries: Australia, Brazil, Canada, China, Finland, Hong Kong, Ireland, Italy, Malaysia, Mexico, Netherlands, New Zealand, Portugal, Qatar, Russia, South Korea, Spain, Switzerland, United Arab Emirates, United Kingdom, and United States by Hore, McAuley and West, (2017). Although no country was established to have achieved the highest rating, however the UK displayed the highest cumulative maturity sum. Meanwhile, the Nigerian government is said to be clueless in this regard according to respondents. It is imperative that the government provides policies and legislations guiding the construction industry towards BIM adoption. This will provide the operational protocol and ensure standardized modelling systems among professionals. Also, this legislation will ensure an industry-wide BIM adoption as many veteran stakeholders are reluctant to change according to respondents will be left without alternatives. Thus, stakeholders will be forced to develop BIM capabilities.

Policy is required to guide the industry, standardize information sharing among professionals, among others. To achieve this, both the government and the industry stakeholders are required to drive the design of peculiar policies tailored to the hurdles in the industry. Stakeholders can help educate the government to eliminate the identified government cluelessness. Respondents mentioned unstandardized protocol and sharing of inadequate information among consultants as a huge hurdle among project teams. This requires collaboration among stakeholders; moving from the traditional isolated approach in the construction process.

4.3 Education / Expertise

There is a limited level of awareness (Ugochukwu, Akabogu and Okolie, 2015; Olapade and Ekemode, 2018b), lack of training, lack of BIM education (Fadason, Danladi and Akut, 2018), discouraging body language of professional bodies, non-inclusion of BIM in school syllabus, among others highlighted by respondents as hurdles to BIM adoption. However, respondents opined that there is a disparity in BIM awareness among professionals; high network individuals and elites are better positioned and thus more aware than others in the industry. This is caused by unequal wealth distribution and financial capacity. Thus, stakeholders are observed to possess different levels of knowledge. Most cannot afford the trainings, workshops and seminars required for develop their capability. The availability of BIM education will demystify the belief of many stakeholders that BIM tools are not flexible and are hard to learn.

Surmounting this hurdle requires the inputs of efforts of all stakeholder at industry, firm and individual levels. Professional bodies need to create awareness, include it in the CPD requirements for their members. BIM education should be made a priority in tertiary institutions that students will be introduced early to BIM. Individual professionals are to make personal efforts at developing expertise on BIM also. Professionals can take advantage of online learning opportunities, workshops, among others.

4.4 Culture

Culture has been identified as one of the challenges faced by the construction industry in developing countries(Ofori, 2001). The traditional approach encourages isolated work approach by professionals in the industry. However, this is against the central requirement for BIM which is collaboration. Due to the culture in the industry, the industry according to respondents is experiencing disparity in knowledge, isolated pockets of adoption and lack of synergy. The presence of the listed hurdles is against the BIM implementation drive.

To overcome this hurdle requires flexibility from industry stakeholders. According to respondents, rigidity by most stakeholders is a major problem. It is a prerequisite that they must let go of the traditional approach totally to achieve total BIM implementation drive. Also, the industry must be receptive to the disruption that this innovation brings.

4.5 Transparency

An established prerequisite for the successful adoption of BIM is collaboration. Collaboration is possible when data integrity is assured; this is dependent on the ability of stakeholders to share credible and reliable data. A study by (Amuda-Yusuf *et al.*, 2017) established a lack of transparency as an important barrier to BIM adoption. However, the study did not elaborate on this factor. Respondents in this study opined that there exists unhealthy ego/ competition among professionals. This is premised on the drive to gain a competitive edge over colleagues, have a large client base, among others. This study identifies that in a bid to gain an advantage over their competitors, many professionals share unreliable data, share inadequate data, among others. Thus, data shared on projects are not deemed reliable to be used by others. This action has brought a lack of collaboration among stakeholders in the industry.

It is worthy of note that the adoption of BIM is an established method of gaining a competitive advantage because of innovation births productivity and value (Ghaffarianhoseini *et al.*, 2016). Moreso, there are other methods of gaining a competitive advantage. The present trend reduces, if not totally strip the industry of the client’s confidence. Firms in the Nigerian construction industry must develop dynamic capabilities that guarantee competitive advantage (Teece, 2017, 2019)

5. CONCLUSION

This study was embarked upon to articulate BIM implementation hurdles in developing countries through an exploratory study to get a deeper understanding of the problems. Although there have been some studies on barriers to BIM adoption previously, it has been observed that nothing has changed. Thus, it can be inferred that either the barriers are yet to be adequately articulated or the exercise of identifying barriers end up on papers and nothing is done to mitigate this. Also, it can be that actions were taken but it was not effective because the hurdles are yet to be properly articulated. Consequently, this study believes that a proper diagnosis of the problem will help with the cure. The study categorizes the hurdles under five categories: they are education/expertise, culture, policy, transparency and infrastructure. The study however identified a rather new barrier that has not been identified by previous studies; this is termed "transparency". Also, the study went a step further by articulating the implications of the hurdles and proffering solutions that are stakeholder specific.

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Visualize GIS, BIM and IoT Data for Comprehensive Green Building Parameters Monitoring

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ABSTRACT: *Green building concept encourages a building to be environment-friendly and energy-saving during its whole life cycle. However, the current green building projects lack an effective visualization system containing multiple sources of data for monitoring and management. The paper presents a novel approach integrating GIS, BIM and IoT data for visualizing Indoor Environment Quality (IEQ) parameters and ameliorating the decision-making process during the asset operational phase. The prevailing green building standards like LEEDS are surveyed and essential parameters are summarized. Moreover, the data sources of these parameters are analyzed and organized. Subsequently, a new pipeline integrating GIS, BIM, and sensor data is proposed to collect, transmit, and visualize the required parameters. The geometry of a IFC BIM model is extracted and transformed into a GLTF 3D model based on WebGL. It is efficiently loaded in the website GIS environment and reconnected with semantic information. IoT data is acquired by connecting with the cloud server and visualized in GIS environment using asynchronous web techniques. A case study is conducted to validate the proposed approach. A campus building is modeled in Autodesk Revit and the sensors are deployed in the realistic building with their exact locations specified in the BIM model. The transformed model is placed in its real-world position in GIS environment and the sensor data is dynamically shown in the interface. In this way, the promising parameters are displayed in the interface along with additional information such as a contextual environment. It implies that such a visualization approach could benefit the green building operational process since it is more comprehensive and intuitive in contrast with traditional approaches.*

KEYWORDS: *BIM, GIS, IoT, Green Building, Indoor Air Quality*

1. INTRODUCTION

The concept of ‘green building’ has stimulated efforts on built environment, including the reduction of energy consumption and natural resource depletion, the decrease of carbon emission, as well as the improvement of indoor environment. Despite the ‘green building’ has been concerned for many years, the Architecture, Engineering, Construction and Operation (AECO) industry has been criticized as a major carbon emitter. There are various considerations to achieve green building, including surrounding factors, building physical factors, energy factors and occupancy factors. These factors have different resources and may be changed during the lifecycle of the building. Therefore, it is a challenge to collect, store and transmit the information properly. In addition, decision-making occurs at all the design, construction and operation and maintenance stages. There is few method and tools to make full use of the collected rich data and translate the data for decision-making support, such as sustainable design and change response. Many researches have explored the use of computer-aided tools to gather, process, and summarize data. However, few studies are about the effort of human experience and intuition on an actionable decision-making. A visualized solution is reliable to support the users to make the data analyses, as well as to fix the judgements obtained by computer-based tools (Ramanujan *et al.*, 2017). The proposed visual analytics tools were mainly used at design and construction phases, but few at operation and maintenance phases (Wong & Zhou, 2015).

BIM emerges as a disruptive technology for the digitalization of AECO industry. It can provide the central database storing the entire information of a built project with 3D geometry representation (Eastman *et al.*, 2011). The specialty of BIM determines that it possesses the potential to support the information storage, management and analysis during the building lifecycle. However, BIM is not omnipotent. The integration between BIM and other technologies, such as GIS and IoT technologies, has been widely discussed in both academia and industry to achieve the extensive applications (Gunduz *et al.*, 2017; Ma & Ren, 2017). GIS is a decision-making supported system equipped with multiple functions of geographic information system. With GIS technology, the realistic world can be expressed through a series of geographical elements and appearances, which normally consists of spatial location reference and semantic attribute information (Peng & Tsou, 2003). In addition, IoT has been an essential technology across many fields of modern day living (Gubbi *et al.*, 2013). It consists of a large range of sensors and actuators, which detect the real word environment seamlessly. Visualization is one of the crucial requirements for IEQ detection in the green building field. Based on the digital representation of integrated building information from BIM technology, the consolidation from GIS and IoT visualization will boost the applicability of green building decision-making system.

Through analyzing the visualization requirements in smart green building management and relational state-of-the-art technologies, this paper aims to propose a novel solution for visualizing BIM, GIS, and IoT data for green building parameters monitoring. The monitoring of IEQ parameters will be developed and discussed particularly. Specifically, in Section 0, the key literature on existing visualization solutions in green building domain and technical challenges of heterogeneous data merging from BIM, GIS, and IoT fields have been reviewed. Section 0 presents the research methodology and Section 0 states a data requirement scheme in order to support the visualized IEQ management system based on the key literature, particular industrial standards, and guidance. The technical roadmap of the multi-data visualization is highlighted in Section 0, with a practical case study in the following section. In the end, we conclude with a brief discussion about the research contributions and future work.

2. LITERATURE REVIEW

2.1. Visualization solution for green building management

The majority of green building visualization tools are utilized in building design and construction phases to implement the energy simulation. Korkmaz et al. state the integrated use of visualization tools, such as Energy 10, SketchUp and Autodesk Revit, during the green building design process (2010). Green BIM are repeatedly emphasized in the researches as an integrated solution for the visualized decision-making system of lifecycle management on the green buildings. However, there are two major barriers of the empowerment of green BIM. One is the limited solution for building O&M stage (Korkmaz et al., 2010; Wong et al., 2015), which implies that the green BIM uses in existing building are rarely discussed. The other challenge is the weak interoperability among various green BIM applications (Lu et al., 2017). To overcome the foresaid challenges, the cross-domain data should be combined organically to realize the wider applications of green building operational decision-making system. BIM, GIS and IoT data are three essential pillars to support the solution, which can reflect the digital presentation of building, urban and environment performance levels (Gubbi et al., 2013; Niu et al., 2015; Tushar et al., 2018). Nguyen proposes an approach to improve the building performance based on the integration of BIM and IoT technologies (2016). In this solution, she includes the knowledge base from the FM (Facilities Management) field and analyzes the IEQ of existing building from the occupants' perspective. The SyncBIM system is designed by Shen et al. to monitor and visualize the air quality condition via BIM and IoT data combination (2019). Recent years, academics are showing increasing interests on the integration of BIM and GIS data from both green building and AECO industries (Kim et al., 2012; Niu et al., 2015; Ronzino et al., 2015). Niu et al. have demonstrated the significance of GIS data in green building visualization system, in order to bridge the data gap between urban and building level energy analysis (2015). Nevertheless, limited number of papers about BIM-GIS-IoT integration within green building management are found, especially about IEQ monitoring area. Gunduz et al. present an ongoing work of the joint use of BIM, GIS and IoT technologies to realize the comfort analysis of the complex facilities (2017). In addition, they also highlight the few studies focus on the collaborative manner within this scope, although it plays a significant role for the efficiency in building performance decision-making system. In this paper, the authors propose a BIM-GIS-IoT visualization approach for green building management and the decision-making. Our method mainly focuses on realizing the IEO parameters monitoring at this stage.

2.2. Heterogeneous data integration

The integration of various sources of data as well as visualizing amounts of data dynamically remain the challenging problems. The difficulty primarily stems from the integration of GIS and BIM data, which are both considerably large scaled, structurally complicated and conformed to specific domains (e.g. geotechnics, construction) (Fosu *et al.*, 2015). A set of works have attempted to fulfill this industry gap. The most popular and intuitive approach is to map data between CityGML and Industry Foundation Class (IFC), which are dominant standards in their respective industries (Kang & Hong, 2015). CityGML uses Boundary Representation (B-rep) to explain geometry properties in XML schema whereas IFC adopts Swept Soild, Constructive Solid Geometry (CSG) and B-rep in EXPRESS schema (de Laat & Van Berlo, 2011). Moreover, the semantic information between them varies a lot in each hierarchy. For instance, the building information in CityGML only contains basic elements such as door and window while IFC encompasses more family categories (Isikdag *et al.*, 2008). A GeoBIM extension has been developed that append IFC data into CityGML context (de Laat *et al.*, 2011). The bi-directional conversion between IFC and CityGML is achieved by developing a unified data model (UDM) that minimizes the data loss during transformation. Yuan and Shen (2010) extend IFC standard to interoperate both GIS and BIM data. Deng et al (2016) propose a mapping approach in different levels of detail using schema mediation and instance comparison. As indicated by Liu et al. (2017), the conversion between CityGML and IFC causes semantics loss and geometry mis-translation due to their distinct properties. Another stream to integrate GIS and BIM data is based on web service. Döllner and Hagedorn (2007) integrate urban GIS with CAD and BIM model on the web. Kong and Hong (2015) propose a GB-ETL method that extracts, transforms and loads BIM data into a Geoserver for Facilities Management. Currently, some GIS service providers such as ESRI start to support loading and rendering BIM model on their 3D GIS service (Liu *et al.*, 2017). Apart from GIS data, the integration of BIM with dynamic IoT data is surveyed by Tang et al. (2019). It is suggested that Service-Oriented-Architecture (SOA) and web services for BIM and IoT integration would be a promising approach. On the other hand, the challenges of interaction with IoT data are not addressed on technical obstruction but on application aspects.

3. METHODOLOGY

This research is based on the review of existing green building visualization and management systems and techniques on heterogenous data integration which could inspire the development of new approaches. A study on international/national green building standards and specifications is then carried out. The key parameters in the operation and facility management stage are summarized and organized in a way the source data can be classified in terms of geospatial data (GIS), building data (BIM) and sensor data (IoT). Afterward, a novel technical approach to visualize various kinds of data is presented. At last, a case study is conducted and the performance is evaluated.

4. GREEN BUILDING PARAMETERS ANALYSIS AND REQUIREMENT

The performance of the green building is determined by many portions, such as energy saving, safety, surrounding environment, facility access and IEQ, where IEQ is the most complex section. There is a dynamic balance between the objective building and environment physical parameters and subjective local factors and occupants' condition, such as culture, expectation and activities to maintain an acceptable indoor environment. Integrated prescriptive measures with more occupant-based requirements are necessary to be considered. Visualized GIS, BIM and IoT data can significantly support the indoor built environment and further environment optimization. Besides, the real time visualized data assists the experts and the occupants to have an in-depth understanding of the indoor environment. It also involves their experience and insight for prediction, monitoring, analysis and adjustment and to create a more flexible and friendly indoor environment beyond the prescriptive measures. There are numerous and detailed green build criteria in terms of IEQ in different standards. Various green building rating system classify and summarize these criteria. This research compares three typical rating systems, Assessment Standard for Green Building China (B/T 50378) (2019), Leadership in Energy and Environmental Design (LEED v4.1) (Llc, 2001) and Building Environmental Assessment Method (BEAM) (BEAM Society Limited, 2012) as well as analyzes their criteria to select the parameters that are desired to consider for maintaining a comfortable indoor environment.

The parameters in the mentioned rating systems can be divided into five main categories, Indoor air quality, Sound, Light, Thermal comfort and Water. Indoor air quality is mainly affected by pollutions, CO and CO_2 emission from parking and kitchen, ventilation. Pollutions and gas emission are determined by air contaminant source, occupied space plan and indoor pressure strategy which can be simulated and predicted based on building design and can be monitored by certain sensors. Ventilation strategy is related with fresh air requirement and ventilation can be detected and controlled by monitoring devices, such as outdoor airflow measuring device, airflow switch and automatic indication device. In addition, LEED presents smoke issues which are mainly controlled by site plan and can be monitored by smoke alarm. Sound is mainly decided by exterior and interior voice sources and the sound insulation performance of the partitions. LEED stresses that the noise comes from HVAC system. Sound level can be measured using the sound level meter or can be assessed using sound transmission class. Besides noise level, LEED presents additional sound requirements, such as reverberation time, and sound reinforcement and masking for functional rooms, like conference room. Vision section contains light quality and vision quality where light includes daylight and artificial light. In principle, it is better to introduce sufficient daylight for energy saving issue when the glare should be controlled by some devices. The glare can be analyzed using vision simulation tool and the location and type of glare control devices can be presented in the BIM model. For the artificial light, the principle is to use multiple light sources to achieve illuminance requirement effectively. LEED stresses the parameter of illuminance ratio, which is related with vison comfort, while GB/T 50378 highlights photobiosafety which indicates the potential hazard of light radiation. It usually uses the simulation tool to obtain a general view of illuminance values. Light meter can also be used on-site, but it is strongly affected by local factors. Therefore, numbers of meters are required for complex situation. Moreover, LEED mentions the lighting controls and quality views which are related with path line and sight line. These parameters concern facility access and occupants' comfort and are usually presented by BIM model. Thermal comfort is affected by temperature, humidity and airflow which can be simulated by building performance simulation tool using the parameters of micro-climate, building physics and occupancy schedule. Apart from this, thermal comfort is also significantly influenced by some local factors, such as occupant activities, culture, local discomfort sources including radiant temperature asymmetry, vertical air temperature difference, floor surface temperature, and drafts. Simulated results are not detailed enough to indicate all the thermal comfort parameters. Therefore, results from on-site transducer are the important supplement to display a relatively complete view of thermal comfort. B/T 50378 adds new parameters about water quality in the up to date version. It proposes the requirements to both the water and water storage equipment. The results are usually referred on test report from the professional testing agency.

In order to efficiently guide further data collection, analyze and visualization. This research re-categorized these analyzed parameters into three groups of GIS, BIM and IoT according to their sources, attributes, data collection methods. The ones affected by surroundings are defined as GIS parameters; the ones affected by building physics and design are defined as BIM parameters; and the ones which can be detected and sensed by the sensors and occupants are defined as IoT parameters.

5. APPROACH

5.1. Overall technical framework

From Section 2.2, there are two predominant alternatives to integrate GIS and BIM data. In this research, the web service-based integration approach is adopted for several reasons. First, either mapping IFC to CityGML or vice versa results in semantic information loss and errors in geometry transformation. Second, schema level GIS document provides limited level of details describing the geospatial environment. However, online GIS service usually provides abundant source of data with real-time or periodically updating, including aerial maps, digital maps and street-side 3D scenes. Additionally, GIS service uploads climate information from satellite, which is closely related to green building operation. Third, web service is easier to connect with cloud server of the equipped sensor. Hence, based on this belief, the technical framework is developed as shown in Fig. 1.

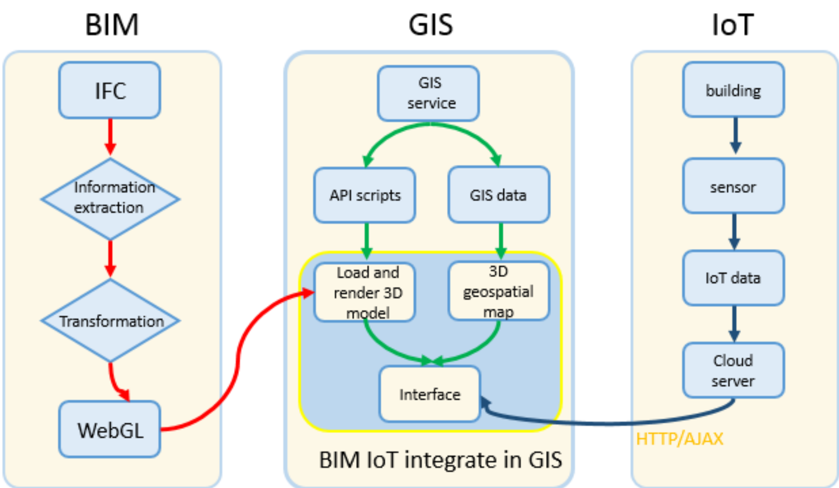

Fig. 1 The overall technical framework of integrating GIS, BIM and IoT data on GIS service

As presented in Fig. 1, the framework constitutes three interrelated blocks: BIM, GIS, IoT, which demonstrates how the data is collected, manipulated and transferred.

- BIM Block: IFC model is exploited as it is the most widely accepted standard in AEC/FM industry (Vanlande *et al.*, 2008). The IFC model is firstly modelled in BIM software and it's processed by toolkits that can parse EXPRESS documents. The semantic and geometry information are extracted separately. The geometry information is transformed into WebGL. WebGL is Web Graphics Library for rendering interactive 2D and 3D graphics in web browser. The semantic information is organized in an independent document containing the demanding BIM family, project and owner data.

- IoT Block: multi-functional sensors are installed in the building with their exact locations registered in the IFC BIM model. These sensors detect the parameters for IEQ in real-time and upload the stream data to the cloud server.
- GIS Block: a GIS web service is employed that allows development upon it. Such service provides GIS data like globe maps as well as API scripts to allow developers to access, manipulate these data and build applications. Consequently, the GIS service could load the WebGL models representing the geometry of BIM with their real-world locations. Moreover, it also enables the ask to sensors' cloud service via HTTP/AJAX protocol and receive the real-time data. Since each sensor is registered in the BIM model, their global coordinates are also known after a set of transformations together with BIM model. In GIS environment, the geometry representation of BIM model can be directly viewed, and sensor data can be visualized in different ways according to purposes of green building operation and management.

Apart from the geometry representation of BIM, semantic information is associated with its geometry in GIS environment. Once a certain part of BIM model is specified in GIS environment, its linked semantic information would be retrieved and visualized.

5.2. Extract, transformation and reconnection of IFC BIM model

As described in the previous section, IFC model should be processed through several steps so as to be fused in GIS environment. The procedure consists of information extraction, data transformation and reconnection. The information extraction step extracts geometry information and semantic information separately. It is ascribed to the fact that through the latter transformation, most of the semantic properties of IFC model would be lost. To preserve such essential information, property information in IFC model should be handled independently and generated a single document in advance. JSON format is adopted taking advantages of its freeform of structure, convenience to parse and retrieve and light size. Hence, the semantic properties of IFC model are recorded according to a data model and a JSON file is thereby serialized. On the other hand, the geometry of IFC model is extracted and converted to pure 3D graphics model. The most commonly seen data types include OBJ, COLLADA and FBX.

The transformation step converts the geometry of BIM into the ultimate 3D model, which is structured based on WebGL. Here, GLTF is chosen as the resulting representation of geometry of BIM. GLTF is a royalty-free specification developed by Khronos Group for the efficient transmission and loading of 3D scenes and models based on WebGL (Khronos, 2015). It has several advantages pertaining to the scenarios of research: (1) it compresses the size of 3D contents by isolating materials, hierarchy, geometry and textures. Thus, the runtime processing on the browser could be efficiently minimized. (2) it has a node hierarchy network to present geometry units and their topology. Intuitively, it is suitable to reflect the topology information in the IFC model. Nonetheless, there is no direct way to convert IFC to GLTF. Existing toolkits and software allow the pipeline IFC-OBJ-GLTF or IFC-COLLADA-GLTF. After a GLTF model is generated, it is loaded by API scripts of GIS web service. The necessary work that must be done is to transform the 3D model from its project coordinate to its real-world global coordinate. The original coordinate could be multiplied by a translation and a rotation matrix to adjust its realistic location and orientation.

Having loaded the GLTF model in the GIS environment, the subsequent step is to link the JSON file containing the properties information to the geometry model. To remain the identity of each BIM family in GLTF geometry model, a small trick is played: at the beginning of transformation step, loop every IfcElement in the IFC model, modify IfcElement.Name = IfcElement.Name + ":/" + IfcElement.ID. It counteracts the condition that the element ID in IFC model could be eliminated during a set of transformation. In the final GLTF model, each geometry unit (node) would contain the original element name. After this manipulation, each node carries its family name as well as it's family ID. For instance, a node in GLTF representing a door element could have a node name "Wood door:/322224". In reconnection, this node name can be easily decomposed using REGEX to acquire its family name and family ID respectively. Once the family ID is obtained, it's geometry can be reconnected to the semantic information by matching the same ID number.

5.3. Sensor data collection and transmission

Air Quality Detecting Sensors are installed inside the building to collect IEQ parameters. They are connected with WIFI and uploading the detected data dynamically to the cloud server. In the GIS service, AJAX is used to retrieve the data from the sensor cloud server asynchronously. By visiting different URL provided by cloud service, different data (e.g. temperature, humidity) in different time or period can be accessed. The data is then visualized in the GIS environment by prevalent web techniques such as HTML and CSS.

6. CASE STUDY

To test the performance of BIM-GIS-IoT integration visualization system on green building management, the Center for Sustainable Energy Technologies (CSET) at University of Nottingham Ningbo China (UNNC) will be investigated building project in this research (see Fig. 2). CSET was completed in September 2008 and it is the first zero carbon emission building in China. Its construction area is 1556m^2, which embraces the functions of design studio and reception hall at ground floor, exhibition area at the first floor, a lab with 15 computers at the second floor and open office area from the third to fifth floors. To meet the goal of zero carbon emission, this building is designed with the green building insight, for instance, passive design, renewable energy utilization and intelligent building control systems. This building is fully used for academic purpose in the recent 10 years, for this reason, its performance can be reflected through monitoring the usage pattern. In this research, the IEQ related parameters are captured as an important element to express the existing environment of the building. Through the innovative visualization of IEQ data in the BIM-GIS platform, the project management team can make much more intuitive decision-making on the various management scheme, such as energy management or building renovation for better practice.

Fig. 2 CSET building

Fig. 3 Lab in the second floor

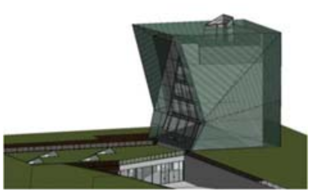

Fig. 4 BIM model of CSET

Fig. 5 Rendered BIM model of Lab

6.1. Building information modeling and sensor deployment

In the project execution process, the data are captured from the fields of building, IEQ and GIS. To establish a digital twin for target building and its context, Autodesk Revit is selected as a building modeling software to present the essential information of the buildings. The LoDs (Level of Details) of the target building and surrounding buildings range between 300 and 350 and only architecture discipline is modeled in this test. For the context buildings, only envelop part are modeled with accurate geometric dimension. CSET BIM model is fully established for validating the value of the proposed technique. In the model, the true geometric and material information of both envelop part and indoor furniture system aligning with the as-built condition. The details of mullion shape have been accurately built to be compliant with the glare control requirements raised in GB/T 50378, LEED and BEAM. Besides, the real placement of furniture can detect the quality of view design through the combination of BIM and GIS data. Fig.2 and Fig.3 show the real-world condition of CSET and the lab on its second floor; Fig. 4 and Fig. 5 show it corresponding BIM model.

To establish the digital environment for IEQ parameters detection based on the real-world condition, it is significant to install sensors appropriately which will perceive the indoor environment in the target building. Five perspectives of IEQ performance have described in Section 0. In this test, the sensors are chosen according to four of the five perspectives, which are indoor air quality, sound, vision and thermal performance. The water quality aspect is excluded in this case, since it needs massive changes of the existing pumping system to be fully monitored accurately. Through market investigation, one supplier can provide one sensor product with seven key IEQ data, which are temperature, humidity, illuminance, sound pressure level, CO_2, formaldehyde and PM10 (shown in Table 1). These parameters can be detected synchronously in one machine, which is convenient for the team to install the sensors and manage the various categories of data.

Seven sensors are purchased for the implementation process. The function analysis and the user pattern of the indoor space are two important evidence to design the sensor distribution. These sensors are installed at every floor of CSET, Fig. 6 shows the location and the naming of each sensor. Fig. 7 and Fig. 8 present the installation condition of the sensor in studio at ground floor (sensor STUDIO 01) and the sensor in exhibition area at first floor (EXHIBITION).

Table 1: Seven parameters of the sensors

Data category	Range	Accuracy	Minimum Unit
Temperature	-40°C ~ 120°C	±2°C	1°C
Humidity	0% RH ~100% RH	±5% RH	1% RH
Illuminance	0lux ~ 9999lux	±5%	1lux
Sound pressure level	30dB ~ 110dB	±5%	1dB
CO_2	0ppm ~ 5000ppm	±(50ppm+5%)	1ppm
Formaldehyde	0mg/m3 ~ 3mg/m3	±5%	0.01mg/m3
PM10	0ug/m3 ~1000ug/m3	±10%	1ug/m3

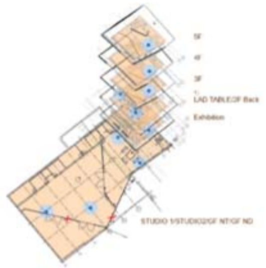

Fig. 6: Sensor deployment

Fig. 7: Sensor Installation (STUDIO 01)

Fig. 8: Sensor Installation (EXHIBITION)

6.2. Performance of data visualization

In implementation, Revit is adopted to extract semantic information and form JSON document by C# programming. IFC OpenShell is used to transform the IFC model to OBJ model. Then OBJ 3D model is processed by the toolkit obj2gltf. Cesium is chosen as a GIS online development platform with open source JavaScript library for high-quality 3D globes and maps (Cesium, 2018). The visualization performance is shown in Fig. 9 and Fig. 10. Fig. 9 presents the indoor environment of CSET, which originates from its BIM model. The left-hand side window presents BIM family information. Once the user clicks a BIM object in the scene, it's related semantic information would be shown. The right-hand side window presents the real-time IEQ parameters. When click one parameter, two charts would appear showing the historical data in the past 24 hours and 45 days. In this interface, the green building manager and engineer could have an intuitive access to sensor data with their locations specified in the environment. Moreover, they could roam in the building and check each BIM family information, which could enhance their experience of monitoring and decision-making.

Fig. 10 presents the outdoor environment where the buildings stem from the BIM model and surrounding environments come from the GIS data. In this scene, the geospatial relationship between CSET and context buildings are clearly shown, and the illumination could be simulated according to time and climate. Through this interface, green building manager and engineer could have a better understanding of surrounding contexts and their influence on the building. In GIS, it is capable to integrate various environment factors that could affect the IEQ. For example, radiation, air quality, water quality and noise could be collected spatial-temporally. The integrated outdoor information with high-resolution 3D maps could benefit green building manager and engineer when analyzing the pattern or source of abnormality of IEQ. However, the integration of full environment parameters is out of the scope of this work.

This visualization system benefits both building users and asset managers for their decision-making process. For building users, they can derive quantitative data showing the dynamic conditions. Instead of making response purely from their body feelings to the built environment, our system provides abundant information for them. For asset managers, the well-interoperated information system allows them to conveniently monitor parameters without visiting multiple documents, cloud service and map. The problems and emergencies could be effectively detected.

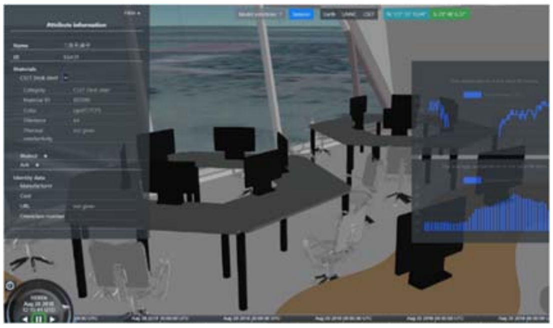

Fig. 9: Performance of visualizing GIS, BIM and IoT data: Indoor environment with BIM family information available

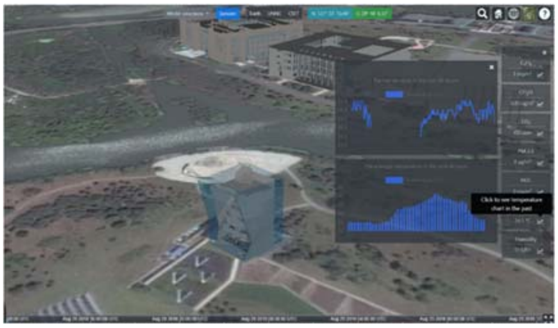

Fig. 10: Performance of visualizing GIS, BIM and IoT data: Outdoor environment with context buildings surrounded

The decision-making process is thereby enhanced by correlating different source of data. Apart from IEQ, our system has potential to be extended to other sections in the field of building operation process, such as smart building. Overall, the promising performance is achieved. In the 3D GIS environment, the geometry and semantic information of BIM along with real-time sensor data installed in the building are visualized. Depending on the requirement of green building parameters monitoring, a new technical pipeline is successfully developed, and relevant parameters are presented in an integrated environment compared to the existing works that are considerably scattered and incomplete.

7. CONCLUSION

This paper presents a novel approach to integrate and visualize GIS, BIM and IoT data for one partition of green building: IEQ parameters monitoring. A study on pervasively adopted IEQ standards is firstly carried out to extract the kernel parameters and grouped them with distinct data source. The results have confirmed that GIS, BIM and IoT could provide unique data respectively. Accordingly, a novel technical pipeline is proposed which integrates BIM and sensor data into 3D GIS environment based on web service. Through a set of transformation, IFC BIM model is turned into a GLTF model and then loaded in GIS environment with reconnection to its semantic JSON document. IoT data is acquired by accessing the sensor cloud service and visualized in GIS with its location registered. A case study is conducted to validate the proposed method. A campus building is modelled in BIM software and sensors are installed in the realistic building. As a result, GIS, BIM and IoT data are successfully visualized with regards to the demanding IEQ parameters. The comprehensive and intuitive data visualization improves green building operation process. The future work would address on developing a holistic platform with feasible system architecture, functions and user interface that could be practically used for a green building project.

8. ACKNOWLEDGMENTS

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Effectiveness of BIM Enabled Modular Integrated Construction in Hong Kong: Applications and Barriers

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ABSTRACT: *In recent years, the Hong Kong government has been actively encouraging the construction industry to use Building Information Modelling (BIM) for enhanced productivity and sustainability. This study has thoroughly examined the effectiveness of BIM for the local MiC industry by identifying the list of potential applications and barriers which are closely examined and discussed. Interviews of local construction experts confirmed the validity of the list, and the subsequent questionnaire survey analysis revealed the relative significance of applications and barriers. The results showed that the use of BIM would be more effective in the design phase rather than the latter MiC project phases. The overall output of this study would facilitate stakeholders in understanding the benefits of BIM-enabled MiC technology for Hong Kong and in formulating better strategies to overcome the barriers towards its successful implementation.*

KEYWORDS: *building information model, BIM, modular integrated construction, MiC, off-site construction*

1. INTRODUCTION

Modular integrated construction (MiC) is a game-changing innovative disruptive technique that transforms the fragmented on-site construction into a value-driven production and assembly of prefabricated modules (Zhai et al. 2019). In a typical MiC project, the prefinished modules (with complete fittings and fixtures) are manufactured in an off-site factory environment and are transported to the construction site for assembly and final installations (Wuni and Shen 2019). The perceived benefits of MiC include shortened construction span, ameliorated labor safety, enhanced construction quality, minimized waste, and improved productivity (Pan and Hon 2018). These advantages make MiC especially suitable for regions dealing with housing shortage problems (Zhai et al. 2019). Hong Kong is one of the world's most densely populated metropolis (Jaillon and Poon 2008) which triggers the development of high rise buildings to address space and dwelling constraints. However, Hong Kong's construction industry faces acute problems such as aging workspace, reliance on expensive local labor, and escalating construction costs. In order to uplift construction productivity and sustainable growth, HKSAR (Hong Kong government) has brought forward MiC as the new policy initiative (Pan and Hon 2018). As a part of the policy, HKSAR has established a construction technology and innovation fund to promote MiC and digitization.

MiC has been an established construction approach in modern countries e.g., Japan, the UK, the USA, Singapore, and New Zealand. Successful delivery of MiC requires three main pre-requisites: 1) consistent information delivery, 2) well-coordination between stakeholders, and 3) smooth supply chain (Zhai et al. 2019). MiC, a relatively new concept in Hong Kong, inevitably necessitates meticulous arrangements from AEC (architects, engineers, and contractors) professionals right from the early stages such as the adoption of new digital technologies aiming to facilitate information exchange during the whole project lifecycle. Building information modeling (BIM) is one such technology that has been promoted by HKSAR for several years. For example, a technical circular issued by the Hong Kong Development Bureau made BIM technology mandatory for capital works projects exceeding HK$30million.

In contrast to the traditional construction, several challenging tasks are encountered in MiC such as the coordination and fabrication of MEP (mechanical, electrical and plumbing) systems particularly in the congested spaces to avoid interference and to comply with the operation criteria (Lu and Korman 2010). BIM appears to be an effective approach to circumvent these challenges. However, the integration of BIM with MiC in Hong Kong is still in the preliminary stages (Darko et al. 2020) and its effectiveness remains to be explored thoroughly. This research, therefore, aims to fill this knowledge gap using literature, interviews, and surveys from local AEC professionals. Rest of the article is organized as follows: Section 2 provides an overview of BIM background in general and its implementation in Hong Kong; section 3 explains the research methodology adopted for this study; section 4 summarizes the applications and barriers of BIM in MiC from the literature review and a case study; section 5 elaborates the details on the interviews from experts to finalize the questionnaire survey; section 6 and 7 presents survey analysis; and section 8 provides the conclusions, recommendations, and future research directions. The overall output of this study would facilitate stakeholders in understanding the benefits of BIM-enabled MiC technology for Hong Kong and in formulating better strategies to overcome the barriers towards its successful implementation.

2. BIM BACKGROUND AND IMPLEMENTATION IN HONG KONG

BIM is commonly defined as a process of generating a virtual 3D model to facilitate data sharing among the construction and design teams. The model contains relevant building data such as precise geometry, design details and specifications, scheduling and estimations, quality of materials, etc. to support the entire project phases including design, on-site installations, and operation-maintenance. Compared to the conventional 2D modeling which depicts graphical entities in terms of lines and arcs, BIM technology enables the formation of smart digital semantic models, containing the complete physical and functional information, of the entire building system including walls, beams, slabs, columns, and MEP systems. In short, BIM creates a visualize model with explicit details to enhance communications and collaborations between designers and builders for successful project delivery. Moreover, BIM allows integrations with other technologies such as Geographical Information Systems (GIS), Radio-Frequency Identification and Geometry (RFIG), and even 3D printer to keep up with the changing innovation requirements.

Since the past few years, HKSAR has been proactively promoting BIM for higher production efficiency and to reduce the on-site labor requirements. The Public Housing Authority (HKHA) has adopted BIM in different ventures for 1) site planning and sequence simulation, and 2) financial control and progress tracking. The Mass Transit Railway Cooperation, Airport Authority, and the Architectural Service Department have also utilized BIM in important projects e.g., Shatin to Central rail link, Express rail link, Midfield Concourse, CX Cargo Terminal, 3D Laser Scanning and Photogrammetry for Heritage Information Management, Kai Tak Nullah Improvement Works, etc. (Poole 2014). Among private developers, some major companies have started hiring BIM professionals extensively and are even expending on equipping their employees with necessary tools and pieces of training to catch up with the advanced development trend. Furthermore, the use of BIM has become mandatory for public projects worth more than HK$30million, following the detailed directive issued by the Development Bureau in December 2017. A revised technical circular was issued a year later in response to the feedback of the Works Department to further enhance the adoption of BIM in public works projects. These initiatives indicate the government's seriousness in the implementation of BIM. Moreover, Hong Kong BIM stakeholders are also collaborating with the CIC towards the strategic adoption of BIM in the Hong Kong construction industry. CIC is using both push and pull strategy to advocate clients and contractors to utilize BIM technology (Poole 2014). This research aims to provide government authorities and the private sector an insight into the possible applications of BIM in MiC and the barriers that need to be addressed through a greater commitment of construction industry stakeholders.

3. RESEARCH METHODOLOGY

This study has taken a systematic research approach (Figure 1), combining the literature review, a case study, interviews, and survey analysis. While the details are mentioned in the relative sections, the overall process can be summarized as follows. Firstly, a thorough literature review was conducted to understand the benefits and issues related to the implementation of BIM in general and then in relation to the MiC industry. This step led to the shortlisting of possible applications of BIM in MiC and the barriers. Secondly, a case study of a BIM-enabled MiC project was carried out to further corroborate the applications from a real project. Thirdly, interviews were taken from four industry experts in Hong Kong to validate the findings from the literature which also led to the finalization of the questionnaire survey. Fourthly, a survey analysis based on the responses of local AEC professionals was conducted to find the relative significance of the shortlisted applications and barriers.

4. BIM EFFECTIVENESS IN MiC

Lawson et al. (2014) reported that the momentum behind MiC popularity in the past decade can be attributed to 1) off-site production of modules during the execution of sub-structure resulting in overall construction time-savings, 2) reduction in labor requirements making the construction site less crowded, improving the working environment and site safety, 3) minimization of usage and wastage of construction materials and re-utilization of modules from dismantled MiC building ensuring sustainability, 4) realization of higher construction quality control, better acoustic and thermal insulation, and fire safety due to the double skin nature of modules, and 5) reduction in noise and disruption during the construction period. Although MiC technology has the potential to deliver several advantages over traditional construction methods but certainly has limitations e.g., requiring higher accuracy in design, better coordination between the project parties, better planning on transportation, etc. To overcome the limitations, BIM integration provides a digital platform to optimize the benefits of MiC technology.

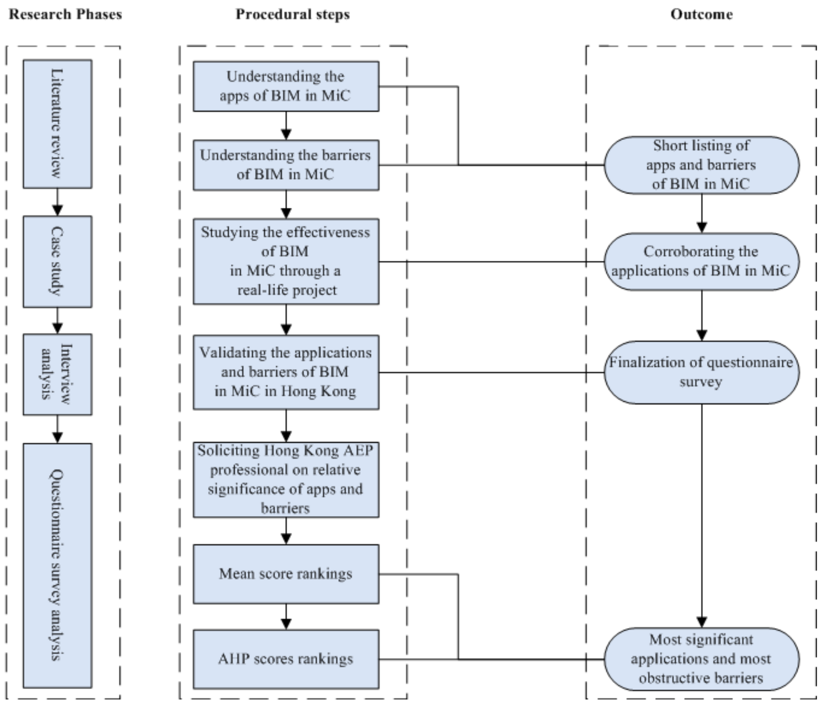

Fig. 1: Research Methodology

4.1. BIM Applications in MiC

4.1.1. 3D Visualization

BIM allows the designer to generate 3D models with the user inputs. At the conceptual phase, the designer can illustrate different 3D models to the client which makes decision making easier at the early stage. Rendering feature generates the pictures of the final product (both internal and external design) which fully resembles the photos as if taken from the real world. If required, BIM has made the whole process of amendments and visualizing the effects of amendments on the final product easier. To facilitate the overall design work, such an early decision making is particularly useful for MiC projects (Johansson et al. 2014).

4.1.2. Clash Detection

In the traditional 2D construction drawing method, clearance of all the clashes between MEP and structure at the design stage is difficult. Clash clearances are typically conducted at the construction stage resulting in variations from the original design (Tatum and Korman 2000). Such variations could be a disaster for MiC projects since the modules are produced off-site, and on-site modifications may lead to cost overruns. BIM clash detection feature helps to sort out the construction clashes in the design phase, thus ensuring an error-free model before off-site manufacturing of modules. For instance, in Aquarium Holton Garden Inn Project, Atlanta, cost-savings, and time-savings were estimated to be US$0.2M and 1,143hrs, respectively, owing to the BIM-enabled detection of 590 collisions between the structure and MEP system in the design phase (Azhar 2011).

4.1.3. Better Communication and Coordination

Goh et al. (2014) reported that BIM enables better communication and coordination among project parties which ultimately improves productivity. In MiC projects, early design completion is a critical success factor for which effective communication is inevitable. BIM creates a central sharing mechanism allowing project parties to work on a single model simultaneously. Ease in updating and exchanging information results in improved interoperate-ability between project team minimizing communication costs and design errors.

4.1.4. Analysis, Simulation, and Optimization

BIM provides analysis and simulation functions such as structural analysis, fire evacuation simulation, lighting simulation, acoustic analysis, energy efficiency analysis, MEP optimization, etc. (Lu and Korman 2010). In the AEC industry, it is common to presume that the tolerance/variation during the execution complies with the design and building codes to eliminate the need for checking (Garrigo et al. 2017). However, the simulations and optimizations in BIM resolve tolerance issues before manufacturing modules. Therefore, through adding such a piece of information in the form of textual data in BIM, the tolerance can be checked effectively.

4.1.5. Parametric Modelling

BIM-based parametric modeling permits the architects to design a model that links every element with its function and other criteria together as a system. Through this function, the designer can create intelligent models which let other parameters to be adjusted automatically when one parameter is changed (Shang and Shen 2014). For example, if a rule is created that the wall shall reach the ceiling height, then the wall height is adjusted automatically in accordance with any change in the floor to ceiling height.

4.1.6. Quantities Take-off and Cost Estimation

In traditional cost estimations, the quantities are measured from a set of drawings such as architectural, structural, MEP, civil, and landscape drawings. The process is not only time consuming but also dependent on the accuracy of the drawings; any discrepancy requires amending the errors and revising the measurements (Andersson 2016). BIM has enabled the quantities to be extracted directly from the model and any revisions can be calculated automatically. This feature, in combination with parametric modeling, establishes a reliable platform for the MiC project to forecast the budget requirements efficiently.

4.1.7. Improved Pre-Fabrication Levels

Due to the discrepancies in traditional 2D drawings, the client generally feels less confident in adopting MiC due to its low error tolerance. The production of error-free BIM models minimizes off-site pre-fabrication risks. Ezcan et al. (2013) argued that a higher level of IT integration is required for streamlining the off-site manufacturing process. BIM provides easy integration with other information systems such as numerically controlled computer machinery to improve the design, detailing, fabrication, and erection of MiC modules.

4.1.8. Scheduling and Logistic Planning

BIM allows the contractor to simulate and evaluate construction sequencing, and coordinate trade activities on site. The project team can identify construction progress at any time and compare the planned schedule with the actual schedule. In MiC projects, with the utilization of BIM, the contractor and manufacturer can coordinate the delivery of modules, determine feasible delivery routes, plan site logistics, and test the delivery plan. BIM can also be used to develop a lifting and hoisting plan for modules. For sites with limited storage, Just-In-Time delivery can be employed through BIM. Further, BIM-RFIG integration can help track the construction sequencing to avoid misplacement of modules (Staub-French et al. 2018).

4.1.9. Assembly Training with BIM

One of the important functions of BIM is to produce walkthrough animations. With the help of BIM 4D models, the construction sequences can be visualized in the form of animation videos. This feature can be used to train workers and operator for a greater familiarization with the construction logistics (BCA 2016). Together with Virtual Reality technology, employers new to MiC execution can experience on-site working in a reality-based simulated environment which may eliminate the possibility of creating costly mistakes (Sampaio 2018).

4.2. A Case Study to Validate the BIM Applications in MiC

The effectiveness of BIM-enabled MiC established through literature was further validated through a case study of a real-life project. A project from Singapore was selected due to the 1) socioeconomic similarities between Hong Kong and Singapore, and 2) vast experience of Singapore in similar projects. North Hill Student Residence Hall, Nanyang Technological University (NTU), Singapore (Sacks et al. 2018) was chosen for this purpose. The project was executed using MiC technology, however, the podium, transfer slab, and the central core were cast using the in-situ concrete construction method. BIM was employed in this project right from the beginning to facilitate the design and to optimize the benefits from MiC throughout the construction phase. The case study analysis found at least six (i.e. 3D visualization, clash detection, parametric modeling, analysis and optimization, communication and coordination, and scheduling and logistics planning) of the nine reported BIM applications. The success of this project proves the usefulness and effectiveness of applying BIM in MiC.

4.3. BARRIERS TO THE IMPLEMENTATION OF BIM IN MiC

4.3.1. AEC Industry Resistant to Change

The construction industry, in general, is not aware of the importance of BIM and hesitant to accept this new technology. The industry is used to 2D drawings of construction methods for ages and considers current software inefficient in handling construction projects. BIM adoption means changing the work environment but most construction companies, not yet convinced of the promised BIM value, are observing the outcomes rather than taking the risks of embracing BIM (Ahmed 2018).

4.3.2. High Initial Cost

In order to adopt BIM, the construction industry not only needs to invest in the software and replacement of hardware to support the software but also in the staff training and professional recruitments. Small and medium enterprises are incapable of bearing such a financial burden. In large companies, shareholders are only concerned about profits and are not willing to invest in a technology that requires large upfront expense but no guarantee of the return (Hasan and Rasheed 2019).

4.3.3. Insufficient Training and Lacking BIM Professionals

Although governments including HKSAR is promoting BIM for several years still the local industry in most countries do not find themselves at ease in embracing such innovative technology. Finding and recruiting BIM experts is difficult due to high salary demands. Salaries offered are sometimes not that attractive to overseas experts. A further dilemma surrounds the fact that not enough academics are trained in BIM and therefore, only a handful of educational institutes offer BIM courses. Companies' reluctance in paying for extra money for employees' training is another hurdle. Generally speaking, as of now, there is a shortage of BIM professionals globally (Sacks et al. 2018).

4.3.4. Legal Responsibilities and Liability Issues

Compared to the traditional contract documents, using BIM raise suspicions on insurance coverage, confidentiality exposure, intellectual property rights and ownership, and model control, etc. For instance, suppose architect, structural engineer, and building service engineer collaboratively produce a model and then pass the final product to the contractor. Later, the contractor might make some amendments to facilitate work with sub-contractors. In case of any unfortunate event in the future, no party would like to be held responsible for the damages and it would be difficult to distinguish the liable party (Lu and Korman 2010)

4.3.5. Lack of Collaborations Between Parties

In traditional construction projects, experts from different disciplines are involved in designing their own parts. However, adopting BIM means putting efforts into collaborating with other project parties but it can be difficult in the sense that each party might be involved in multiple BIM projects simultaneously. Architects, engineers, etc. in such a case would prefer the subordinates to complete the design first rather than discussing with other parties each time a discrepancy arises (Staub-French et al. 2018).

5. EXPERTS' INTERVIEWS AND FINALIZATION OF QUESTIONNAIRE

In order to validate the findings in relation to MiC technology in Hong Kong, structured interviews of four highly experienced local AEP experts were carried out (Table 1). All the four experts were involved in the construction industry for more than 10 years, and have at least 1 year of BIM experience. Three experts, including two architects and one structural engineer, were working in the public sector, whereas one expert was employed as a BIM specialist in a private architect firm. Such knowledgeable and experienced experts provide the necessary credibility to the interview results. Experts were asked to provide feedback on the list of applications and barriers with respect to the implementation of BIM in the Hong Kong MiC industry. As a general rule of thumb, it is established that any application/barrier failing to acquire at least 50% consensus from the experts will be excluded from the list. Agreements and remarks of experts about each application and barrier are given in Table 2. In summary, experts 1, 2, and 3 agreed that applying BIM in MiC would be highly effective for the Hong Kong construction industry since this technology integration would facilitate 1) early coordination and confirmation of design, and 2) the subsequent production and fabrication in a factory. Expert 1 stated that BIM usage in MiC would result in quicker and more sustainable construction. Expert 4 also agreed on the effectiveness of BIM in MiC, however, pointed out that BIM is more effective in the design stage than in the construction stage, therefore, BIM may not meet governments' expectations. Besides, some functions such as 'analysis, simulation, and optimization' and 'scheduling and logistic planning' require extra work in inputting a substantial amount of data to maximize benefits. From the interview analysis, all the applications and barriers were found satisfactory to be included in the questionnaire survey for further validation and analysis.

Table 1: Background information of experts

Experts	Organization	Occupation	Experience in the Construction Industry	Experience in BIM
Expert 1	Public Sector	Architect	10-20 years	1 year
Expert 2	Public Sector	Architect	10-20 years	4 years
Expert 3	Architect Firm	BIM Specialist	10-20 years	17 years
Expert 4	Public Sector	Structural Engineer	10-20 years	6 years

6. QUESTIONNAIRE SURVEY

An online questionnaire is conducted to solicit professionals from Hong Kong AEC industry on the significance of applications and barriers. Professionals were selected on the basis of their experience in the construction industry and their emails were collected through companies' websites, snowball techniques, and personal requests to the HR departments. Professionals were first, asked to rate the applications and barriers on a Likert scale of 1 to 5, with 1 being 'less effective' and 5 being 'very effective'. Secondly, due to the fact that in the Likert scale questions, respondents rate single factors without considering the relative importance of other factors, the experts were also asked to rate applications and barriers with respect to other applications and barriers on an AHP scale for analytical hierarchical process analysis. Email invitations were sent to the professionals; 47 professionals chose to respond to the survey. Most of the respondents were government officials i.e. 35. Out of the remaining, 8 were consultants and 4 were contractors. Professionals represented diverse fields of expertise, the highest number of respondents were quantity surveyors i.e. 15. Besides, architects, structural engineers, building service engineers, and building surveyors represented the rest of the groups of professionals. Around 70% of the experts had more than one year of work experience in BIM (Table 3).

7. SURVEY ANALYSIS

7.1. Mean Score Ranking Technique

The well-established technique of mean score ranking was used to rank the factors (Tariq and Zhang 2020). In this technique, the average score of ratings given by respondents on each factor is calculated using the formula:

$$\text{Mean score} = \sum_{i=1}^{N}(f_i \; x \; S_i)/N \text{ , } 1 \leq \text{Mean Score} \leq 5$$

Where N = no of respondents; f = frequency of ratings (1-5) given by the respondents on ith factor; S = score given by the respondents on ith factor. The threshold mean value for the most significant factors is taken as 4. As an example, 32 experts rated 'clash detection' as 5, 7 rated it as 4, and 8 others rated as 3. The overall mean score as a result came out to be 4.51.

7.2. Analytic Hierarchy Process

Analytic Hierarchy Process (AHP) is a structured technique developed by Prof. Thomas L Saaty in 1970 for decision making by quantifying the weights of criteria (Triantaphyllou 2000). This method utilizes the experts' experience through pair-wise comparison of each factor/criterion. A nine-point scale is typically used for AHP to determine the significance of one factor/criterion over the other. A comparison matrix is then developed from the respondents' pair-wise ratings which are normalized in the next step. The average normalized scores are used to rank the factors/criteria in the final step, as shown in Figure 2. To simplify the questionnaire, this research assumed that the respondents' decisions are consistent and used only one factor for pair-wise comparison with other factors. Pair-wise scores of all the other factors with each other are then calculated using geometric mean values (GMV). The average of normalized GMVs was then used to sort out the significance order.

Table 2: Experts' Agreement on applications and barriers of BIM in Hong Kong MiC industry

Functions	Agreement					Remarks
	Expert1	Expert2	Expert3	Expert4	Consensus	
Applications of BIM in Hong Kong MiC industry						
3D Visualization	✓	✓	✓	✓	100%	Expert 2 regarded 3D visualization a common and useful application for all types of projects including MiC.
Clash Detection	✓	✓	✓	✓	100%	All the experts stated that this function would help to minimize the design errors in the initial stages.
Better Communication & Coordination	✓	✓	✓	✓	100%	Expert 2 shared that this function is facilitating his construction team greatly in a current MiC project.
Analysis, Simulation, and Optimization	✓	✓	✓	✓	100%	Expert 4 believed that this function is useful but highly time-consuming because all the manual data needs to be inputted in BIM.
Parametric Modelling		✓	✓	✓	75%	Expert 1 mentioned that the benefits of this function are not so obvious and can be used for a less complex system.
Assembly Training with BIM			✓	✓	50%	Experts 3 and 4 suggested that this function can enhance the worker's readiness on working in MiC projects through watching animations. Contrary to this, expert 1 disagreed and said that the actual implementation can only be learned through hands-on experience. Expert 2 pointed to the fact that the local contractors are experienced in pre-fabrication works and dealing with MiC would not be much problem.
Quantities Take-off and Cost Estimation	✓	✓	✓		75%	Expert 1, 2, and 3 agreed that this function can assist quantity surveyors in taking off quantities quicker but modifications and standards are required for accurate measurements. Expert 4 showed his disagreement by commenting that not everything can be measured through BIM such as reinforcement.
Scheduling and Logistic Planning	✓	✓	✓	✓	100%	All the experts showed 100% agreement on this function, however, they stated that not everything goes as planned especially due to traffic congestion and unforeseen events.
Improved Pre-fabrication Level	✓	✓	✓	✓	100%	All the experts agreed that BIM can lead to an improvement in the prefabrication of modules by producing accurate drawings and by integrating advanced mechanical fabrication technologies with BIM. However, experts also asserted that fabricators in Hong Kong are highly experienced so this benefit is not so obvious.
Barriers to the BIM implementation in Hong Kong MiC industry						
Insufficient Training and Lacking BIM Professionals	✓	✓	✓	✓	100%	Experts regarded this barrier as one of the most critical barriers due to which Hong Kong is far behind in implementing BIM than many developed countries.
Legal Responsibilities& Liability Issues	✓	✓	✓	✓	100%	All the experts agreed on the significance of this barrier.
High Initial Cost	✓	✓	✓	✓	100%	Experts mentioned that the license fee is expensive and Hong Kong companies generally are not willing to invest in the training of their employees.
AEC Industry Resistant to Change	✓	✓	✓	✓	75%	All the experts agreed on the significance of this barrier. They stated that the BIM trend will ultimately take over and will change the current industry culture and contractual relationships between the project stakeholders.
Lack of Collaborations between Parties	✓	✓	✓		75%	Same as the previous remark.

7.3. Most significant applications and barriers

Mean score values and AHP values of BIM applications and barriers are given in tables 4 and 5, respectively. From table 4, it can be noted that 'clash detection', '3D visualization', and 'better coordination and communication' are the most significant factors as per the mean score rankings. These rankings are consistent with the interview analysis as all the interviewees agreed on the importance of these applications. However, there are some differences in means score and AHP rankings. AHP suggested 'clash detection' and 'better coordination and communication' as the two most significant applications; and ranked 'analysis, simulation, and optimization' higher than '3D visualization'. This is due to the opinion of some experts believing that '3D visualization' is a common application and should not be regarded as a special application for MiC. Nevertheless, '3D visualization' should be regarded as an effective application as its benefits are direct. To obtain benefits from 'analysis, simulation, and optimization', huge data is needed to be inputted which means extra workload.

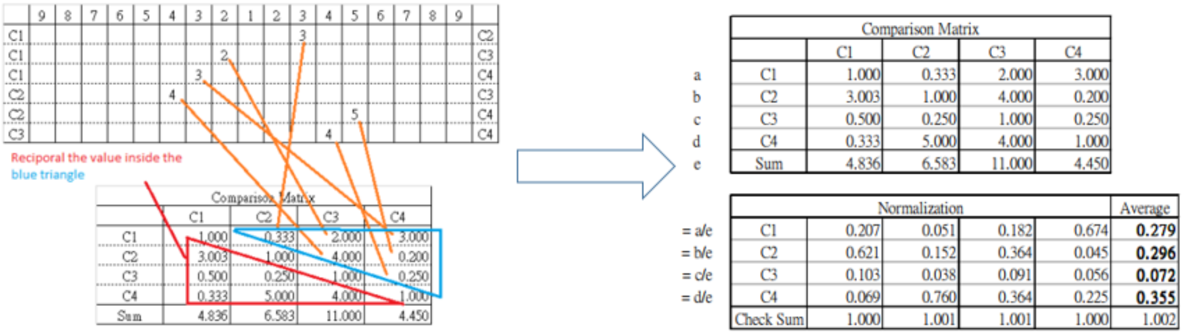

Fig. 2: AHP based calculation of average scores and rankings

Table 3: Background information on local AEC professionals

Background Questions	Responses	No. of respondents	Percentage
Type of organization	Government	35	74.5%
	Consultant	8	17%
	Contractor	4	8.5%
Professional fields	Quantity Surveying	15	31.9%
	Architecture	13	27.7%
	Structural Engineering	8	17%
	Building Service Engineering	6	12.8%
	Building Surveying	5	10.6%
Working Experience	Less than 10 years	39	83%
	10-20 years	7	14.9%
	More than 20 years	1	2.1%
BIM Experience	Less than a year	14	29.8%
	1-2 years	27	57.4%
	2-5 years	5	10.6%
	5-10 years	1	2.2%
	Total	47	100%

Table 4: Ranking results of BIM applications in Hong Kong MiC Industry

BIM apps in MiC	Mean score values	Rank	AHP values	Rank
3D Visualization	4.19	2	0.11	4
Clash Detection	4.51	1	0.19	1
Better Communication and Coordination	4.17	3	0.17	2
Analysis, Simulation, and Optimization	3.70	4	0.13	3
Parametric Modelling	3.06	5	0.10	5
Quantities Take-off and Cost Estimation	2.68	6	0.09	6
Improved Pre-Fabrication Level	2.23	8	0.07	7
Scheduling and Logistic Planning	2.32	7	0.07	7
Assembly Training with BIM	2.19	9	007	7

From table 5, 'insufficient training and lacking BIM professionals' and 'high initial cost' came out to be the most obstructive barriers from both types of ranking techniques. The mean score value of 'high initial cost' is very close to 4, therefore it is also regarded as one of the most obstructive barriers. These ranks are also consistent with the interview analysis.

In addition to scaled survey questions, the AEC professionals were also asked to comment on the overall effectiveness of BIM in the Hong Kong MiC industry. More than 60% of the AEC professionals believed that BIM-MiC integration would be effective, and the remaining 40% suggested otherwise. The reasons for disagreement might be similar to those suggested by the interviewees that BIM is focused more on the design stage, and benefits in the later stages are not direct requiring extra work. This general bias can also be confirmed from the rankings of the applications focusing on the construction stage such as 'scheduling and logistic planning' and 'assembly training with BIM' are lower than the applications focusing on the design stage.

Table 5: Ranking results of the barriers to the implementation of BIM in Hong Kong MiC Industry

BIM barriers in MiC	Mean score values	Rank	AHP values	Rank
AEC Professionals Resistant to Change	3.55	3	0.14	4
High Initial Cost	3.94	2	0.26	2
Insufficient Training and Lacking BIM Professionals	4.15	1	0.30	1
Legal Responsibilities and Liability Issues	2.83	5	0.10	5
Lack of Collaborations Between Parties	3.47	4	0.19	3

8. CONCLUSIONS, RECOMMENDATIONS, AND FUTURE RESEARCH

This research conducted a thorough investigation of the effectiveness of applying BIM in the Hong Kong MiC industry. The applications and barriers were established first through literature. A case study analysis of NTU's student residential hall is carried out to further explore the applications of BIM in MiC. The findings were then validated through structured interviews from four field-experts. After finalizing the questionnaire survey as per the interview results, the relative significances of applications and barriers were identified through a questionnaire survey analysis based on the responses of local AEC professionals. Interview and survey results revealed that BIM would be more effective in the MiC design stage than the later stages. The most effective applications were: 'clash detection', '3D visualization', and 'better communication and coordination'. And, the most obstructive barriers were: 'insufficient training and lacking BIM professionals', and 'high initial cost'.

Based on experts' suggestions, recommendation on BIM's adoption in Hong Kong MiC industry can be summarized as to 1) provide more training to the AEC professionals in educational institutes and in the industry; 2) offer governmental incentives to the industry such as GFA concession, tax waiver, extra technical scores, etc.; 3) share benefits from the real cases to the construction industry professionals; 4) establish an online platform for knowledge sharing and technical support, and 5) collaborate with Autodesk and other developers to make the software user-friendly and tailor-made to the specific needs of the Hong Kong such as merging the functions of BIM in a single software.

Although this article explored the BIM effectiveness in MiC through the combination of literature, case study, interviews, and survey there were certain limitations to the research design. Firstly, only 1 case study was conducted and that too was not from Hong Kong. Secondly, only 47 respondents completed the questionnaire; a large sample size would have given more credibility to the results. Based on the limitations, future research will firstly, try to incorporate local case studies and secondly, more experts having vast experience in BIM will be invited to participate in the survey. Comparison with other advanced countries will also be beneficial to provide recommendations on the improvement of the existing industry situation in Hong Kong.

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The Perceived Impact of Building Information Modeling on Construction Performance

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ABSTRACT: There are plenty of research on the benefits of BIM. However, previous research mainly discuss the general benefits of BIM theoretically. Even objective evidence to evaluate impact of BIM on construction performance is provided in some research, limited qualitative and quantitative indicators are included. This paper aims to improve the existing research by evaluating the impact of BIM on construction performance with a comprehensive performance framework. Specifically, this study provides evidence of how business type, building types, delivery methods, and project value impact BIM-assisted project performance. A survey was designed to collect the objectively empirical evidence through 95 BIM contractors worldwide. First, profiles of the practitioners, their projects, and companies are summarized by analyzing their demographic information. Then, BIM-assisted project performance is compared among different business types, building types, delivery methods, and project values between projects with means of project performance.
KEYWORDS: *Construction Performance; Building Information Modeling; Stakeholders; Construction Delivery.*

1. INTRODUCTION

Construction projects delivered in traditional method face issues such as schedule delay and cost overrun (Shane et al., 2009; Gu, Singh and London, 2015). Building information modelling (BIM) is advocated as a method to assist project schedule and cost management such as BIM 4D and 5D model (Li, Xu and Zhang, 2017). However, limited data or evidence is provided to prove BIM's benefits and support its adoption. Studies with substantial theoretical justification and data support are needed to justify the benefit return of the investment on BIM. There is no shortage of studies on the benefits of BIM. However, many studies are limited to theoretical discussion without empirical evidence (Succar, Sher and Williams, 2012). As for studies providing empirical evidence, some studies only provide qualitative data analysis, but they are very limited in evaluating BIM-assisted project performance quantitatively (Bryde, Broquetas and Volm, 2013; Eadie et al., 2013). In addition, studies provide quantitative focus on limited indicators (Suermann and Issa, 2009; Kelly and Ilozor, 2016). Therefore, there lacks a comprehensive evaluation of BIM's benefits from both qualitative and quantitative aspects. This study aims to improve current research about BIM impact on project performance by proposing a comprehensive formwork. The objectives of this study are 1) the development of comprehensive framework including both qualitative and quantitative indicators, and 2) the validation of proposed framework by surveying contractors worldwide.

2. LITERATURE REVIEW

Previous studies use either qualitative or quantitative indicators to measure BIM-assisted project performances. However, limited studies employ a comprehensive framework including both qualitative and quantitative indicators to measure BIM-assisted project performance. For instances, studies only employ qualitative indicators to measure BIM-assisted project performance (Suermann et al., 2009; Eadie et al., 2013). However, qualitative indicators are not reliable to measure project performance (Cox, Issa and Ahrens, 2003), and quantitative indicators should be provided as well. Studies including quantitative indicators to measure BIM-assisted project performance focus on limited indicators (Kelly and Ilozor, 2016). Also, objectively empirical evidence proving impacts of BIM implementation on project performance is uncommon (Succar, Sher and Williams, 2012). In addition, previous studies discovered that business types (Khanzode, Fischer and Reed, 2008), building types (Chen, Dib and Lasker, 2011; Porwal and Hewage, 2013), different delivery methods (Mollaoglu-Korkmaz, Swarup and Riley, 2013; Carpenter and Bausman, 2016) and project values (Chan, Scott and Chan, 2004) can impact project performance. However, no study comprehensively evaluates how business types, building types, delivery methods, and project value impact BIM-assisted project performance. Therefore, this study aims to provide empirical evidence to evaluate how business types, building types, delivery methods, and project value impact BIM-assisted project performance by using a comprehensive framework to measure performance of BIM-assisted performance.

3. METHODOLOGY

The study mainly consists of three parts, which is proposing BIM-assisted project performance measurement indicators, data collection, and data analysis. First, project performance indicators are identified through literature review, including 12 quantitative indicators and 25 qualitative indicators. Then, a questionnaire is designed and distributed to experts with BIM-assisted project experience online. Finally, data is analyzed to disclose the difference of BIM-assisted project performance among different business types, building types, delivery methods and project values.

3.1 Project Performance Indicators

25 qualitative indicators and 12 quantitative indicators are proposed based on literature review as shown in Table 1. Among 15 qualitative indicators, five of them are used to evaluate project performance, with one more indicator evaluating overall project performance. 20 of qualitative indicators are used to evaluate project management performance with one more indicator evaluating overall project management performance. 12 indicators are proposed to evaluate project performance quantitatively.

Table 1. Indicators to evaluate project performance

Qualitative project performance indicators	**Qualitative project management (PM) indicators**			**Quantitative project performance indicators**	
Cost Goal	Labor Management (e.g. lost time, idle time)	Information Management	Safety Management	Total number of design errors	Total cost of punch list items
Schedule Goal	Subcontractor Management	Communication Effectiveness	Joint Solutions	Total number of request for information (RFI) during Pre-Construction	Total number of near misses
Quality Goal	Cost Management	Communication Method	Leadership	Total number of RFI during Construction	Total number of site accidents
Safety Goal	Schedule Control	Communication Frequency	Stakeholder Coordination	Total number of change orders	Total number of legal claims and litigations
Customers' Satisfaction	Work Progress	Coordination Tools	Decision-Making Process	Total cost of change order	Total cost of legal claims and litigations
Overall project performance	Quality Management	Open Information Sharing	Scope Clarification	Total cost of rework	Total number of repeat customers
	Earlier Detection of Problems	Material Management (e.g. waste reduction)	Overall PM performance		

3.2 Data Collection

The questionnaire was distributed in 2018. The population of this study was global academic and industrial professionals who have experiences in construction projects. A total of 8,000 qualified professionals were identified by personal contacts, social media, and professional associations. The questionnaire was distributed by individual invitation and with the assist of professional associations. The associations who distributed questionnaire to their members included Associated General Contractors (AGC), the American Institute of Architects (AIA), the Central Automated Building Association (CABA), Construction Owners Association of America (COAA), and National Association of Women in Construction (NAWIC). Moreover, data collected from those with no experience in BIM-assisted projects was not used to ensure data quality. Finally, 95 valid responses were received. The questionnaire contains three parts. The first part gathers organization information at which the participants work. The second section collects participants' experience related to BIM-assisted project. The third part collects participant's evaluation on the performance of projects with and without BIM.

3.3 Data Analysis

Data analysis includes three parts, which are descriptive analysis, qualitative indicator analysis, and quantitative indicator analysis. Descriptive analysis summarizes the profiles of practitioners, their projects, and companies. Qualitative indicator analysis and quantitative indicator analysis disclose BIM-assisted project performance between different business types, building types, delivery methods, and project values for projects with and without BIM. Quantitative indicators are measured by ratios (BIM-assisted projects/Non-BIM-Assisted Projects) of different items and qualitative indicators are measured based on seven-Likert scale.

3.3.1 Descriptive Analysis

The descriptive analysis results show profiles of respondent's companies and projects they had been involved in. The sample covers different business types, with 67% general contractor, 27% construction manager and 6% MEP. Fig. 1 shows profiles of delivery methods of BIM-assisted projects that participants have participated in, with 31% design-build (DB), 27% construction management (CM) at risk, 20% design-bid-build (DBB), 13% integrated project delivery (IPD), 7% construction management (CM) agency. The profiles of building type among these projects are shown in Fig. 2, with 26% commercial, 19% healthcare, 17% educational, 11% industrial, 11% institutional, 10% residential, and 6% transportation.

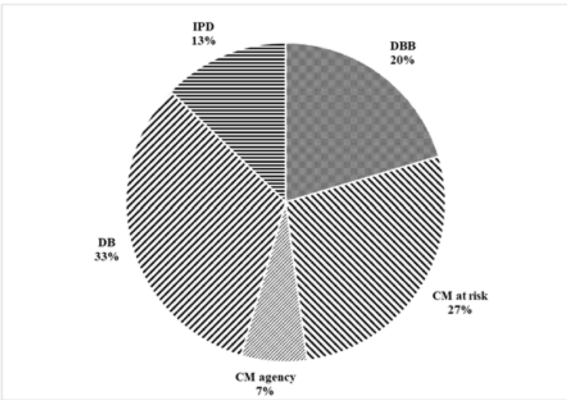

Fig. 1: Summary of respondents' projects by project delivery method

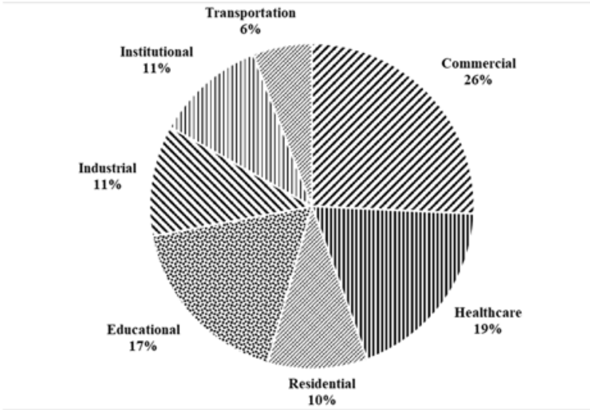

Fig. 2: Summary of respondents' projects by building type

3.3.2 Analysis of Qualitative Indicators

The participants were asked to compare project performance and project management (PM) performance with and without BIM based on a seven Likert-scale, in which one means much worse, four means no change, and seven means much better. This part aims to analyze participants' qualitative evaluation of overall project performance and overall PM performance by different business type, building type, delivery method and project value.

Fig 3 shows participants' evaluation of project performance and PM performance by business type. General contractor's evaluation of project performance and PM performance are higher than construction managers' evaluation. Moreover, evaluation of participants involved in Mechanical, Electrical, and Plumbing (MEP)-related projects is highest, with 6.32 for project performance and 6.08 for PM performance. It is because MEP project consists of more challenging tasks and the implementation of BIM can address these problems (Fischer, Engineering and Reed, 2008; Chen, Dib and Lasker, 2011).

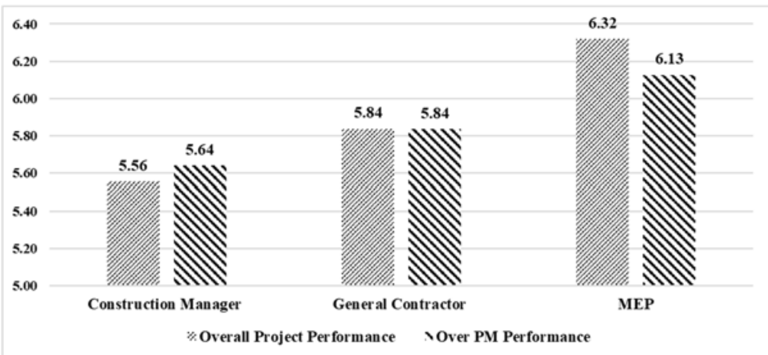

Fig 3: Overall project performance and PM performance by business type

Fig 4 shows participant's evaluation by building type. For overall project performance, residential projects (6.11) have best performance, then follows transportation (6.01), institutional (5.94), industrial (5.92) and healthcare (5.92). For the PM performance, the resident projects are highest as 5.93, then follows 5.92 for healthcare, 5.91 for institutional. The residential projects have highest PM performance and project performance. Moreover, there is a large gap between project performance and PM performance in transportation projects. The project performance is 6.01, however, PM performance is 5.77, which may be because BIM has been employed to solve major problems in infrastructure (i.e., aging and deterioration), but more collaboration between academia and industry is needed to improve adaption of BIM transportation projects (Costin et al., 2018). Healthcare projects also have both a high project performance and PM performance, which may be because various MEP systems are involved in those projects (Chen, Dib and Lasker, 2011).

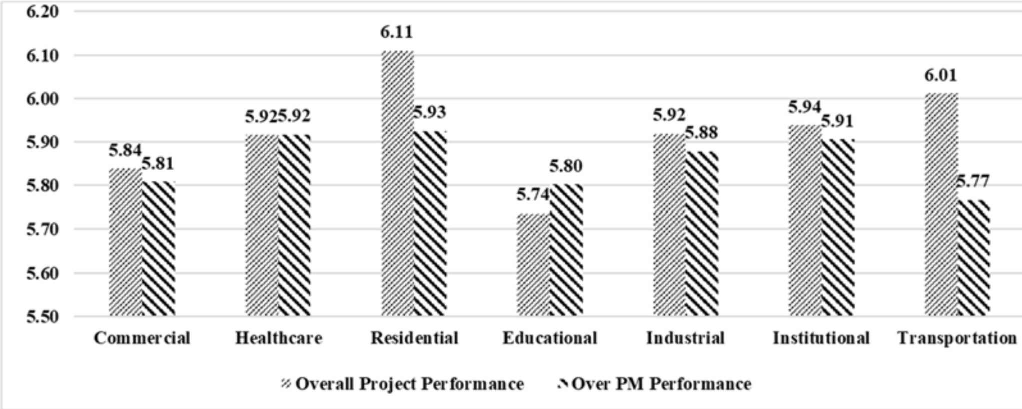

Fig 4: Overall project performance and PM performance by building type

Fig 5 shows participant's evaluation by project delivery method. As for project performance, construction management (CM) agency (6.01) is the highest, then follows Integrated Project Delivery (IPD) with 5.94 and Design-Bid-Build (DDB) with 5.93. As for PM management, CM agency (5.93) is still the highest, then follows by 5.85 for Design-Build (DB), 5.83 for IPD and DB. CM agency, which is the most appropriate method for the owner, has the highest project performance and PM performance (Mahdi and Alreshaid, 2005). IPD is a new method in which architects, engineers, contractors, developers, clients, and manufacturers can work more closely than other methods (Fanning et al., 2014). Although previous studies conclude that IPD is the best delivery method to implement BIM (Nasrun, Nawi and Hamid, 2015), both PM performance and project performance are not the highest. "Other" includes participants involved in G-Max and design-assist delivery method. They have the second highest project performance and highest PM performance.

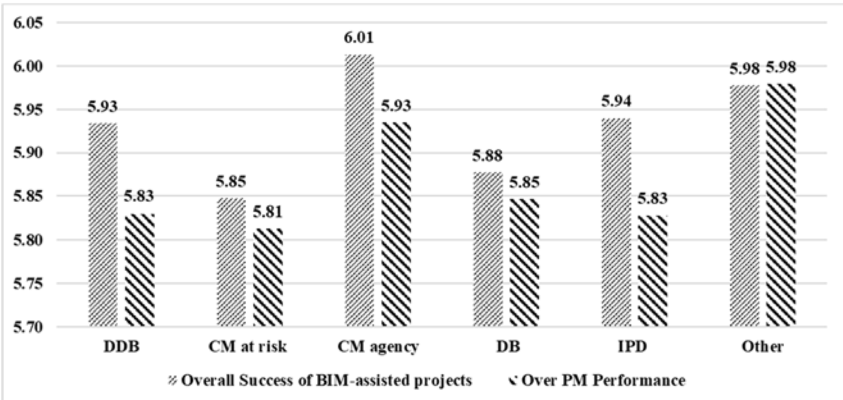

Fig 5: Overall project performance and PM performance by project delivery method

Fig 6 shows participant's evaluation by project values. Projects with \$10 million to \$20 million values (6.07) has the highest project performance, then follows by larger than \$100 million (5.83), \$50 million to \$100 million (5.80). As for PM performance, projects with \$10 million to \$20 million (5.95) are highest. However, project performance and PM performance with value less than \$10 million are related low among all projects, which is because those company mainly involved in small contractors are fear to change, and cost of training and hardware upgrade may be a barrier for them (Gledson, Henry and Bleanch, 2012).

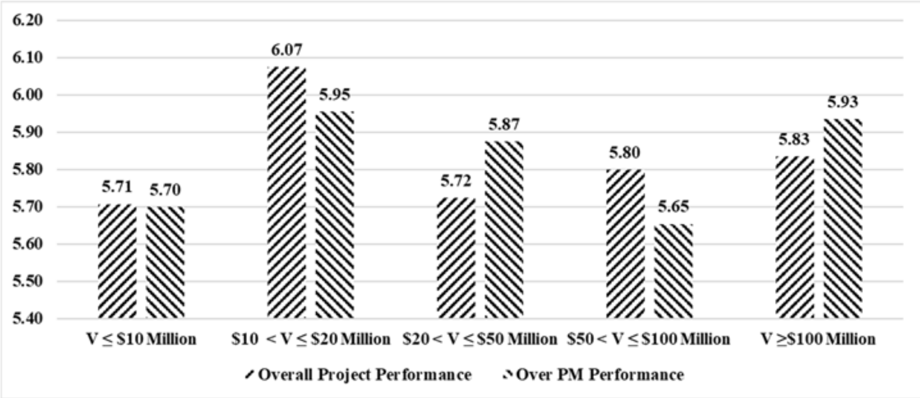

Fig 6: Overall project performance and PM performance by project values.

3.3.3 Analysis of Quantitative Indicators

This part discusses participants' responses to 12 quantitative indicators. Participants were asked to indicate the ratios for 12 items. For example, if most of BIM-assisted projects that one participant has been involved in had 80 design errors and most of non-BIM-assisted projects that one participant has been involved in had 100 design errors and, then the ratio of total number of design errors is 0.8, which equals (80/100). Median of each quantitative evaluation item is calculated because mean is sensitive to large numbers. There are 44 participants not responding to these questions, so their quantitative evaluations were replaced by median of other respondents.

Fig 7 shows quantitative evaluation of project performance by building type. Generally, performance of all projects has been improved because no ratio is larger than 1. It concludes that implementation BIM increase project performance from several phases. For the preconstruction phase, number of design errors and request for information (RFI) decrease in all types of buildings with the use of BIM. For construction phase, cost of rework and cost of change order (CO) has reduced dramatically. It may be because constructability of design is analyzed in BIM before construction, which reduces rework in construction phase (Hui-Hsuan et al., 2013). However, number of repeat customers do not increase with the implementation of BIM.

Fig 7: Quantitative evaluation of project performance by building type

Fig 8 shows quantitative evaluation of project performance by delivery methods. Projects delivered by all these methods can benefit from BIM, because no ratio is larger than 1. CM agency and IPD methods benefit most from BIM, which is consistent with finding from qualitative analysis. CM agency benefit most from BIM among all delivery methods, which may be because BIM help clients better manage all contractors (Mahdi and Alreshaid, 2005). Though IPD methods is a related new method for managing projects (Kent and Becerik-Gerber, 2010), it benefits most with the implementation of BIM. Among all these quantitative indicators, cost of rework reduced most.

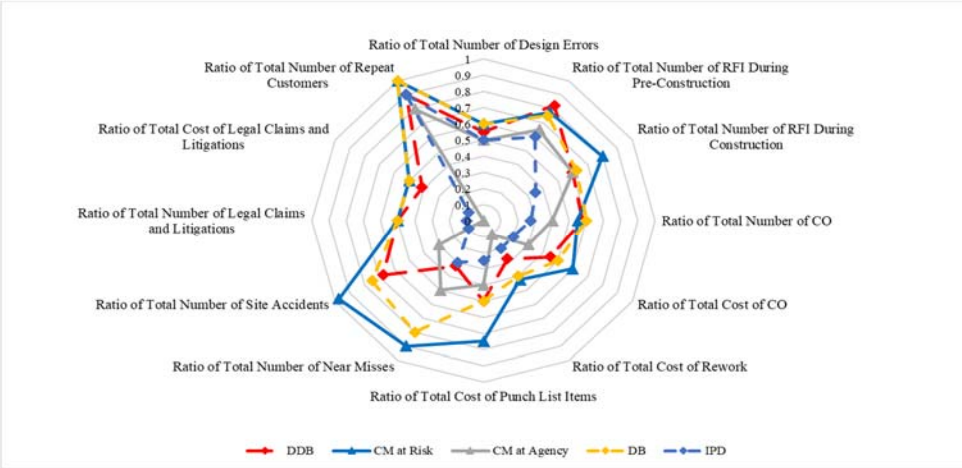

Fig 8: Quantitative evaluation of project performance by delivery method

As shown Fig 9, most projects can benefit from BIM. Projects with value between 40 million to 100 million benefit most from BIM. Projects with value less than 10 million do not change a lot with the implementation of BIM, which is consistent with finding from qualitative analysis. As for repeat customers, projects with value between 20 million and 40 million and more than 100 million increased with implementation of BIM.

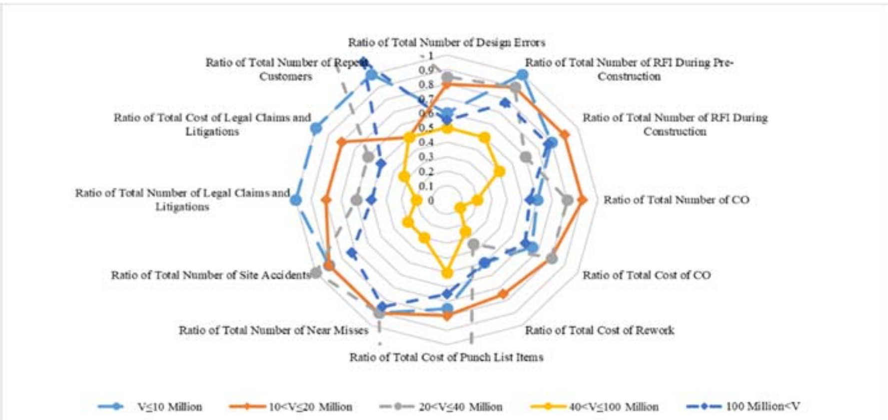

Fig 9: Quantitative evaluation of project performance by project value

As shown in Fig 10, participants work as construction manager think projects benefit more from BIM from quantitative analysis. It may be because construction managers are involved in more aspects of construction, while general contractors focus on construction phases. Therefore, construction managers have a more comprehensive understanding of how projects benefit from BIM among different phases, which results in higher evaluation.

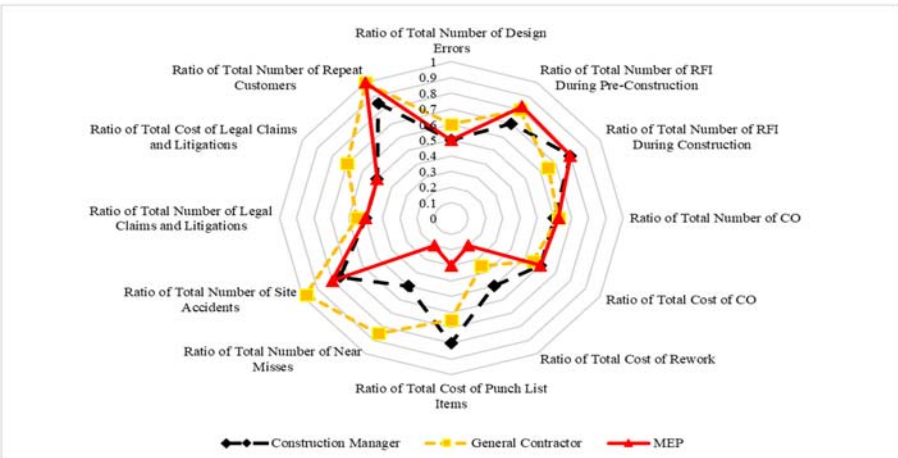

Fig 10: Quantitative evaluation of project performance by business type

4. DISCUSSION AND CONCLUSION

This paper provides empirical evidence to compares how business type, building type, project value and delivery method impact BIM- assisted project performance through survey with 95 contractors by comprehensive framework to evaluating BIM-assisted project performance both qualitatively and quantitively. The results of qualitative indicators show that project performance is improved with the implementation of BIM. Among different building types, the residential project has been improved most. As for delivery method, the project delivery method of CM agency is improved the most with the implementation of BIM. However, the performance of BIM-assisted projects with IPD is not ranked the highest. As for business type, people worked MEP systems think projects benefit from BIM most. The results of quantitative evaluation show cost of rework reduce most with the implementation of BIM. However, ratio of repeat customers is not significantly higher with the implementation of BIM, which is inconsistent with finding from previous study that BIM can improve customer-client relationship (Azhar, Khalfan and Maqsood, 2012). Moreover, CM agency and IPD are the relatively more effective than other methods in improving BIM-assisted project performance. As for project value, small projects may suffer from hardware upgrade cost (Gledson, Henry and Bleanch, 2012), which results in no significant improvement from the BIM. However, evaluation from construction managers and general contractors are different in qualitative and quantitative evaluation, which may be because they are involved in different construction activities.

The findings of this study have both theoretical and practical contribution. Theoretically, this study provides more insights into how business type, building type, delivery method and project value impact BIM-assisted project performance. Practically, this study provides practitioners with more information about how to implement BIM in projects. The implementation of BIM should take into business type, building type, and delivery method into consideration. In addition, CM agency and IPD should be chosen for BIM-assisted projects because they are more effective to improve project performance.

The limitation of this study is that the study mainly focuses on how general contractors and construction managers evaluate BIM benefits. However, other participants such as architects and engineers should be involved to get a more comprehensive understanding of how BIM impacts projects. In future, as hardware develop fast these years, new study should be done to exam how development of hardware impacts BIM-assisted project performance. Also, follow up survey should be conducted to explore why BIM-assisted projects have better project performance.

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Dimensional Quality Assessment of Prefabricated Housing Units Using 3d Laser Scanning and Bim

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ABSTRACT: *Prefabricated construction has been popularly adopted worldwide. To ensure the smooth and successful installation of prefabricated components on-site, it is important to conduct a geometric quality inspection for prefabricated components. However, traditional quality inspection methods are labor-intensive, time-consuming, and error-prone. Therefore, this study develops an automated geometric quality inspection technique for prefabricated housing units using BIM and LiDAR. The proposed technique collects the 3D laser scan data of the prefabricated unit using a LiDAR, which contains accurate as-built surface geometries of the prefabricated unit. On the other hand, the BIM model of the prefabricated unit contains the as-designed geometries of the unit. The scan data and BIM model are then automatically processed to inspect the geometric quality of individual elements of the prefabricated units. For an element, the inspection checklist includes the dimension of the element and the dimension and position of openings. To validate the proposed technique, experiments were conducted on two prefabricated bathroom units (PBUs). The inspection results show that the proposed technique can provide accurate quality inspection results with 1.1 mm accuracy. In addition, the experiments also show that the proposed technique greatly improves the inspection efficiency regarding time and labour.*

KEYWORDS: *Prefabricated housing units; Geometric quality inspection; BIM; Laser scanning*

1. INTRODUCTION

Prefabricated construction is getting increasingly popular in the building and construction industry for the past decades. Prefabricated construction, considered as an innovative and cleaner construction approach, can significantly improve construction productivity (Li et al., 2016), reduce construction time (Arashpour et al., 2015), and minimize construction wastes (Arashpour et al., 2016). Therefore, prefabricated construction has been highly recognized by the global construction industry and increasingly popular among the AEC industry in different countries and regions.

The assembly of prefabricated components is the main activity during the construction stage. The geometric quality of prefabricated components impacts the productivity of installation most, because unexpected construction delays and system failure can occur if the geometric qualities of prefabricated components are poor (Kim et al., 2019). Thus, management of the geometric variability is a major challenge for prefabrication construction (Shahtaheri et al., 2017). For example, construction delays and additional costs for repair or replacement are required if there are serious dimensional defects or volumetric defects on prefabricated units at the manufacturing stage of an off-site construction project (Josephson and Hammarlund, 1999). Therefore, geometric quality inspection of prefabricated components in factory plays an important role in prefabrication construction.

In order to guarantee the geometric quality of prefabricated components, traditional inspections are usually conducted manually. For example, measurement tapes are used to inspect the dimensions of different prefabricated components, and a straight edge and a slip gauge are used for flatness inspection of concrete surfaces. However, manual inspection is usually labour intensive, time-consuming, and error-prone, especially when the amount of prefabricated components becomes large. Therefore, an automated geometric quality inspection technique for prefabricated components is needed to improve the efficiency and accuracy of geometric quality inspection.

In the past decades, building information modeling (BIM) and light detection and ranging (LiDAR) have been widely applied to address various issues in the AEC industry. BIM, which contains rich geometric and semantic information of buildings and civil infrastructures, is commonly used for data storage, visualization, and management of building elements throughout the project lifecycle. LiDAR, which is also known as 3D laser scanning, can obtain 3D point cloud data of objects with a high speed and high accuracy using infrared

laser-based measurement techniques. LiDAR has been popularly adopted for various applications including surface defect detection (Tang et al., 2010a), dimension estimation (Wang et al., 2016), construction progress monitoring (Kim et al., 2013), and as-built BIM reconstruction (Tang et al., 2010b). Despite the previous studies, there is still a lack of research on geometric quality inspection of prefabricated components using BIM and LiDAR.

This study aims to develop an automated geometric quality inspection technique for a specific type of prefabricated components, namely prefabricated housing units, using BIM and LiDAR. The 3D laser scan data of prefabricated housing units are acquired with a LiDAR, and the as-built geometries of the structural elements of the prefabricated housing units are automatically extracted using the developed algorithms. By comparing the as-built geometries with the as-designed ones in BIM, the geometric quality is assessed based on certain tolerance values.

2. CHECKLIST FOR GEOMETRIC QUALITY INSPECTION OF PREFABRICATED HOUSING UNITS

In order to carry out the geometric quality inspection of prefabricated housing units, the inspection checklist and tolerance for each item in the checklist should be identified. Therefore, according to the Construction Quality Assessment System (CONQUAS) stipulated by BCA, the geometric quality inspection checklist and the corresponding tolerance of prefabricated housing units are summarized in Table 1. For each structural element such as a wall panel, the checklist items include dimension, opening dimension, and opening position.

Table 1. Geometric quality inspection checklist and tolerance of prefabricated housing units

Checklist items	**Tolerance**
Dimension	Depending on the edge length L: $L \leq 3$ m: ±6 mm; 3 m < $L \leq 4.5$ m: ±9 mm; 4.5 m < $L \leq 6$ m: ±12 mm; Additional allowable tolerance for every subsequent 6 m: ±6 mm
Opening dimension	+10 mm
Opening position	±25 mm

2.1 Dimension

Dimension inspection is the most common and important item for the geometric quality inspection of structural elements. Measurement tapes are usually used to conduct dimension inspection. It is common that the actual dimensions of prefabricated structural elements are slightly different from the as-designed dimensions. However, the dimension variation should be within an acceptable tolerance.

For the structural element shown in Figure 1, the dimensions are measured as the lengths of all the four edges such as L1 to L4. The tolerance value depends on the length of edges. If the edge length L is no more than 3 m, the tolerance value is ±6 mm; if the edge length L is between 3 m and 4.5 m, the tolerance value is ±9 mm; if the edge length L is between 4.5 m and 6 m, the tolerance value is ±12 mm. For an edge length L longer than 6 m, the tolerance value increases by ±6 mm for every subsequent 6 m.

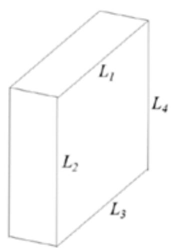

Fig. 1. Measurement of dimensions (e.g. L1 to L4) of a structural element

2.2 Opening dimension

Openings are often needed on prefabricated structural elements to enable the insertion of MEP services. To ensure proper installation and connection of MEP services, the dimensions of openings must conform to the designed blueprint. The dimensions of an opening are measured as the lengths of all the opening edges (e.g. d1 to d4 in Figure 2), traditionally by a measurement tape. The tolerance value for opening dimension is ±10 mm according to the regulation.

2.3 Opening position

The positions of an opening are also important for proper installation and connection of MEP services. As shown in Figure 2, the positions of an opening are measured as the distances from edges of the opening to the edges of the structural element, such as p1 to p4. The tolerance value for opening positions is ±25 mm according to the regulation.

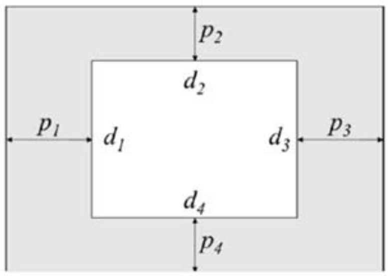

Fig. 2. Measurement of the dimensions (d_1 to d_4) and positions (p_1 to p_4) of an opening on a structural element

3. PROPOSED GEOMETRIC QUALITY INSPECTION TECHNIQUE

3.1 Data acquisition

Data acquisition aims to acquire the laser scan data of the prefabricated unit to be inspected. It is essential to carefully determine the scanning parameters so that the acquired data fulfil the needs of quality inspection while the scanning time is minimized. As a result, before the acquisition of laser scan data of the prefabricated housing unit, scan planning is performed in the following two steps.

Step 1: Determination of required scan data quality. To ensure reliable quality inspection results, the scan data must have enough quality with regard to accuracy and spatial resolution. The accuracy of scan data is measured as the ranging error of individual scan point between the measured and actual points. Spatial resolution of scan data is measured as the distance between two adjacent scan points, and the spatial resolutions (ssh and $ssvv$) in horizontal and vertical directions can be different for a terrestrial LiDAR. Assuming that a scan point is measured with a ranging error of 5 mm, the resulted object location measurement can have 5 mm error. Similarly, when the spatial resolution of scan data is 5 mm, the resulted object dimension measurement will have an average error of 5 mm because object edges cannot be accurately estimated. Therefore, the required scan data accuracy and spatial resolution depend on the allowable object location and dimension estimation error. As discussed in Section 2, the checklist items for prefabricated housing inspection have tolerance values between 6 mm and 25 mm. After interviewing site engineers from prefabricators and contractors, it is suggested that the acquired scan data should have an accuracy of ±2 mm and spatial resolution of 2 mm in both directions.

Step 2: Determination of scanning parameters. After determining the required scan data quality, proper scanning parameters are determined to make sure the acquire scan data achieve the required quality. The scanning parameters mainly include the scanning device, scanning angular resolution, and scanning location. The scan data accuracy is determined by the scanning device and scanning location. Different LiDAR systems have different ranging accuracy depending on the working principle and hardware performance. A typical terrestrial LiDAR has a ranging accuracy between 1 mm and 10 mm. For a specific LiDAR, the ranging accuracy also differs when the scanning locations are different. In general, to guarantee a high scan data accuracy, short distance DD and small incident angle $\alpha\alpha$ are desired. However, a trade-off between scan data quality and scanning time is needed.

3.2 Data pre-processing

Raw laser scan data obtained from a LiDAR always contain unwanted data from objects other than the target. For example, although only scan data near the target object (a prefabricated unit) are selected as shown in Figure 3(a), the selected data still contain unwanted data from the roof, floor, and other objects (Figure 3(b)). Hence, it is necessary to remove these useless data before further processing.

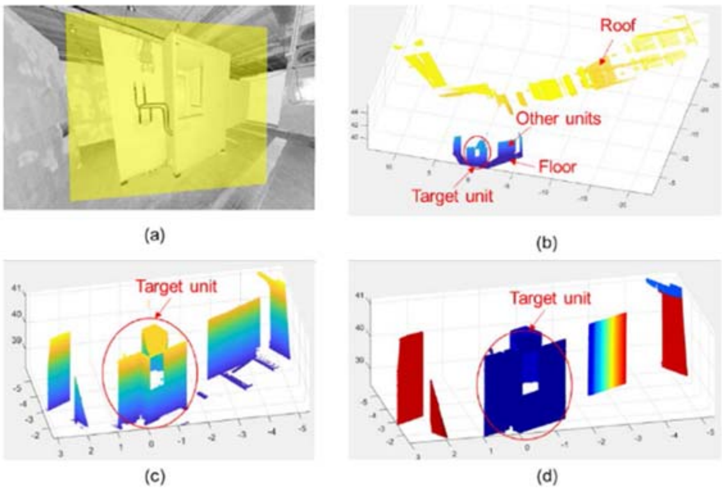

Fig. 3. Data cleansing: (a) selection of scan data surrounding the target unit, (b) 3D view of the selected scan data, (c) scan data after removing the roof and floor, and (d) extraction of the target unit using region growing.

Because the floor and roof are planar objects, the random sampling consensus (RANSAC) algorithm is adopted to find the two planes. By setting the normal vector of the plane to be vertical (i.e. normal vector [0, 0, 1]), two planes representing the floor and roof are recognized and then removed from the scan data. The remaining scan data represent the target prefabricated unit and other nearby units, as shown in Figure 3(c).

To differentiate the target prefabricated unit and other units, the region growing algorithm is adopted to segment the scan data into multiple clusters. The region growing algorithm initiates a cluster from a seed point, and then iteratively examines the neighbouring points of the seed point or newly added points. If the distance to the neighbouring point is less than a threshold value, this neighbouring point is added into the cluster. In this way, the cluster continuously grows until no more neighbouring within certain distance can be found. Here, the threshold value should be set to be larger than the required spatial resolution (2 mm) of scan data. As scan data representing the target unit have a spatial resolution of 2 mm, all the data for the target unit will be extracted as one cluster. On the other hand, because scan points from two different units are not connected, different prefabricated units become different clusters. As shown in Figure 3(d), the scan data are segmented into multiple clusters shown in different colours, and the cluster with the most scan points is the target prefabricated unit.

3.3 Geometric quality inspection

3.3.1 Extraction of as-built surfaces and edges

To inspect the checklist items, the as-built surfaces and edges of structural elements need to be extracted from scan data. For each as-built surface, its approximate location is known based on the location of the corresponding as-designed surface in BIM. Therefore, scan points close to the as-designed surface are extracted and a planar surface is extracted from these scan points using the RANSAC algorithm. For example, three planar surfaces are extracted from scan data as shown in different colours in Figure 4(a).

Each surface usually has four outer edges at four sides, and might have additional edges if an opening exists on the surface. Each edge can be viewed as the intersection of two surfaces. If the two surfaces defining an edge are both scanned, this edge (known as type I edge) can be extracted as the intersection line of the two planar surfaces.

However, if only one surface is scanned, this edge (known as type II edge) cannot be extracted as the intersection line and should be extracted using the following method. For each type II edge, scan points along the edge are extracted based on the location of the respective as-designed edge, as shown in Figure 4(b). Then, the last scan point in each row or each column is identified for edge estimation. Usually, for a vertical edge, the last scan point in each row is identified, and for a horizontal edge, the last scan point in each column is identified.

However, the actual edge is not exactly falling on the last scan points. Instead, the actual edge should fall between the last scan points and the points next to them, which are actually outside this surface. As shown in Figure 4(c), one virtual point (shown as dashed points) is manually created in each row next to the last scan point by assuming that the spacing between two points is constant. It can be inferred that this virtual point must be outside the surface. Hence, the actual edge must be between the last scan point and this virtual point. Then, the middle points between each pair of last scan point and virtual point are obtained as edge points (red crossing in Figure 4(c)), and this edge is represented by these edge points to facilitate the calculation of inspection checklist.

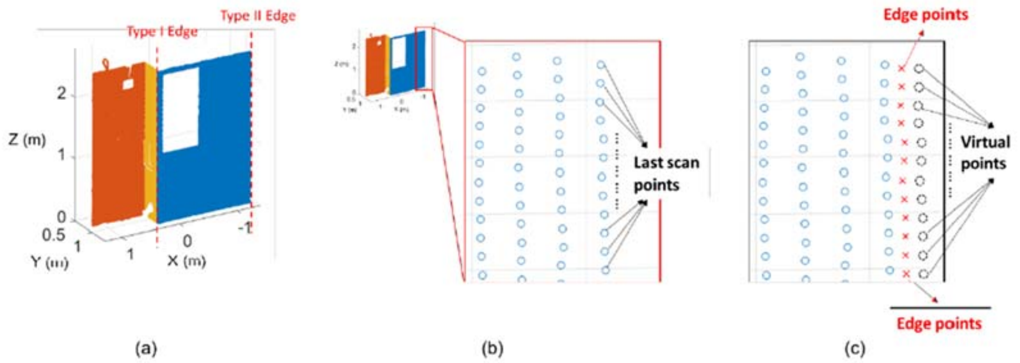

Fig. 4. Extraction of as-built surfaces and edges: (a) extraction of surfaces, (b) extraction of last scan points in each row/column for an edge, and (c) estimation of an edge as a set of edge points.

3.3.2 Checklist Calculation

In the extraction of as-built surfaces and edges, each surface is represented as scan points falling on it (denoted as surface points) and each edge is represented as a set of edge points. In this step, all the items in the inspection checklist are calculated based on these surface points and edge points.

For the dimensions of elements and the dimensions and locations of openings, the surface points are projected onto the least-squares fitted plane of all surface points. Then, each edge line is estimated as the least-squares fitted line of the respective edge points. Next, the corner points of each element and each opening are extracted as the intersection points of edge lines. Then, the dimensions of elements or openings are calculated as the distances between corner points, and the locations of openings are calculated as the perpendicular distances from corner points of openings to the edge lines of the element.

4. VALIDATION EXPERIMENTS

This study conducted experimental validation on two PBUs manufactured in a Singapore prefabrication factory, as shown in Figure 5. The overall size of each PBU was around 2.5 m (length) × 1.8 m (width) × 2.4 m (height). The PBUs were manufactured using precast concrete for walls and floors. In addition, each PBU had a few cylindrical MEP elements (pipes) made of PVC. For PBU A, the quality inspection scope was the three structural wall panels (shown as S1 to S3). Similarly, for PBU B, the scope was the three structural wall panels (shown as S4 to S6). Among the structural wall panels, S3 and S6 had an opening on each of them. As the experimental process is similar for both PBUs, this section presents the experimental process of PBU B only.

Fig. 5. Two PBUs for validation experiments

A FARO Focus S70 terrestrial laser scanner was used to collect scan data. This scanner had a measurement range from 0.6 m to 70 m, and a ranging accuracy of ±1 mm at 25 m. Therefore, this scanner could fulfill the ±2 mm accuracy requirement for PBU inspection. Next, the scanner locations and angular resolutions were determined to achieve a spatial resolution of 2 mm in both directions.

After data acquisition at the optimal scanning location, the scan data were processed through data pre-processing and geometric quality inspection. Figure 6 shows the data processing procedures of PBU B. First, the noise data were removed from the raw scan data and the scan data for PBU B were aligned with the BIM model after a coordinate transformation, as shown in Figure 6(a). Next, the three planar surfaces (S4 to S6) of PBU B were extracted as shown in Figure 6(b), and each structural element was inspected based on the checklist and the surfaces and edges extracted from scan data.

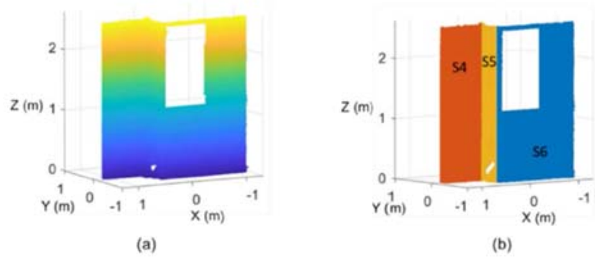

Fig. 6. Experimental process for validation experiments: (a) scan data for PBU B after data pre-processing, and (b) extraction of three planar surfaces S4 to S6 for geometric quality inspection.

To examine the accuracy of the proposed technique, the checklist items obtained from the developed technique were compared to the ground truths, which were obtained from manual measurement using traditional inspection methods.

Table 2 shows the inspection discrepancies for all the structural elements (S1 to S6) regarding all the checklist items (dimension, opening dimension, and opening position). It is worth noting that the values shown in Table 2 are the average of the absolute values of the discrepancies for each checklist item. For example, for the dimension of a structural element, the inspection discrepancies for its four edge lengths were calculated, producing four inspection discrepancies. Then, the average of the absolute values of the four inspection discrepancies was calculated and is shown in Table 2. The calculation process is similar for other checklist items. According to Table 2, the inspection discrepancies for structural elements are ranged from 0.5 mm to 1.6 mm, and the overall averaged inspection discrepancy is 1.2 mm. In general, the average discrepancy of 1.2 mm indicates that the developed technique is accurate enough to provide reliable geometric quality inspection results for structural elements.

It is also observed that S2 and S5 had relatively small inspection discrepancies among all the structural elements. It is partially because S2 and S5 had relatively smaller sizes than other structural elements. In addition, S2 and S5 intersected with other structural elements. Thus, the vertical edges of S2 and S5 were type I edges, which were more accurately estimated compared to type II edges.

In addition, the efficiency of the developed technique was compared to the traditional inspection methods. Using the developed technique, it took 8 minutes to collect scan data and 1 minutes to run the developed data processing algorithm to obtain all the checklist items for each PBU. In the whole process, only one worker was needed to operate the LiDAR and run the algorithm. On the other hand, using the traditional inspection methods, it took around 20 minutes to complete the inspection for one PBU, and two workers were needed to conduct the inspection because many measurements could not be accomplished by only one worker. Therefore, it is concluded that the efficiency of geometric quality inspection can be greatly improved using the developed technique. The needed inspection time was reduced from 20 minutes to 9 minutes for each PBU, and the needed labour was reduced from two workers to one worker only.

Table 2. Inspection discrepancies between the developed technique and ground truths for the checklist items for structural elements

Structural Element	Inspection Discrepancies (mm)		
	dimension	opening dimension	opening position
S1	1.5	N/A	N/A
S2	0.6	N/A	N/A
S3	1.3	1.2	1.5
S4	1.2	N/A	N/A
S5	0.5	N/A	N/A
S6	1.6	1.4	1.0

5. CONCLUSIONS

Prefabricated construction has been popularly adopted worldwide because it improves construction productivity, sustainability, and safety. To ensure smooth and successful installation of prefabricated components on site and avoid construction delays and system failures, it is important to conduct geometric quality inspection for prefabricated components before they are shipped to construction site. However, the traditional quality inspection methods using traditional measurement devices are labour intensive, time-consuming, and error-prone. Therefore, this study develops an automated geometric quality inspection technique for a specific type of prefabricated components, namely prefabricated housing units, using BIM and LiDAR.

The proposed technique is implemented in five steps. First, the proposed technique uses a LiDAR to obtain the laser scan data of the as-built prefabricated units. Scan planning is implemented before data acquisition to make sure the acquired data fulfil the needs of geometric quality inspection. Second, data pre-processing is conducted to remove noise data from raw laser scan data and then register the scan data with the as-designed BIM. Next, the structural elements of the prefabricated units are inspected after identifying the as-built surfaces and edges and comparing to the as-designed ones. The inspection checklist of a structural element includes the dimension of the element, and the dimension and position of openings.

To validate the proposed technique, this study conducted experimental validation on two PBUs manufactured in a Singapore prefabrication factory. The PBUs were manufactured using precast concrete for walls and floors. The proposed technique was implemented on the two PBUs for geometric quality inspection. To examine the accuracy of the proposed technique, the checklist items obtained from the developed technique were compared to the ground truths, which were obtained from manual measurement using traditional inspection methods. It is found that the inspection discrepancies between the proposed technique and ground-truths are ranged from 0.5 mm to 1.6 mm, and the overall averaged inspection discrepancy is 1.1 mm. Overall, the averaged inspection discrepancy of 1.1 mm indicates that the proposed technique can provide accurate geometric quality inspection results prefabricated housing units. In addition, experimental results also show that the proposed technique can greatly improve the inspection efficiency.

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VDC Scorecard: Evidence-Based Understanding of VDC from 108 Projects

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ABSTRACT: *Virtual design and construction (VDC) is the use of multidisciplinary information models for improving project performances in the construction industry. Prior studies have addressed and suggested the critical factors of VDC that help improve performances, but this often was done descriptively in the form of qualitative or subjective judgment, case studies, interviews, or literature review. This research (1) formulated seven hypotheses relevant to the critical factors that support VDC performance based on literature review, (2) collected data through VDC Scorecard from 108 projects across the world in 13 different countries in North America, Europe, and Asia, and (3) used the statistical techniques to check the validity of the critical factors. The analyses of the data showed that five of the seven hypotheses are valid with quantitative evidence—showing that these factors support VDC performance. The five critical factors with the evidence are metrics, cross-organizational sessions, integrative delivery approaches, the maturity of product, organization, and process (POP) models, and the coverage of a product model. The two factors without the evidence are technical & collaborative methods and the integration of POP models—the evidence of the relationship between these two factors and VDC performance is not as strong as that of the five factors. Further analyses of the data showed that the industry invests in the technologies of VDC but its investment is not fully translated into performance improvement. This can be interpreted as a sign of inevitable disruption often observed in a transforming stage of innovation and adopting advanced technologies.*
KEYWORDS: *Virtual design and construction; Building information modeling; Construction management; Project management; Assessment; Evaluation*

1. INTRODUCTION

Virtual design and construction (VDC) is the use of multidisciplinary product, organization, and process (POP) models for improving project performances and achieving business objectives (Kunz and Fischer 2009). The definition of VDC can be similar to that of building information modeling (BIM), but for those who interpret BIM as product modeling (e.g., "digital representation of physical and functional characteristics of a facility" (NIBS 2007)), the definition of VDC is broader than BIM as VDC encompasses organization and process modeling in addition to product modeling, as well as automation, and optimization with the goal of achieving business objectives.

VDC and BIM were introduced to the architectural, engineering and construction (AEC) industry in the early-2000s (Kunz and Fischer 2009; Laiserin 2002) and since then the adoption to the industry has been growing rapidly (McGraw-Hill Construction 2012, 2014a; b). In keeping with the pace, research communities have also been active in the development of assessment frameworks for evaluating VDC or BIM of an organization (AIA California Council 2007; Gao 2011; Kam et al. 2017; NIBS 2007), and many of them have taken cues from a maturity model that originated from the software industry (Paulk et al. 1991) for developing their frameworks.

These VDC (including BIM) assessment frameworks often acknowledge and, during the assessment, measure the factors that help improve VDC performances. For instance, a framework may measure the use of integrated concurrent engineering (an example of a factor that helps improving VDC performance), by which the project team wishes to accelerate an engineering schedule (an example of VDC performance improved by a factor), and the improved VDC performance, in a longer run, will likely translate into improved project performance (i.e., on-time delivery of the project). However, the effectiveness of these factors or the correlation between such factors and VDC performance has not been statistically analyzed. Analyses of these factors in previous studies are mostly descriptive: they are based on qualitative or subjective judgment, case studies, interviews, or literature review.

For this research, we developed a VDC assessment framework—the VDC Scorecard—capable of quantitatively measuring the critical factors (supporting VDC performance) and the VDC performance (that should be improved by the critical factors). Then we hypothesized the correlation between the critical factors and VDC performances and, for conducting statistical analyses against the hypotheses, applied the VDC Scorecard to 108 projects to accumulate enough sample size. In comparison to prior studies on critical factors supporting VDC performance, this research is the first attempt to take quantitative and evidence-based approaches to validating the critical factors based on large scale data (108 projects across 13 countries).

2. THE VDC SCORECARD DEVELOPED FOR DATA COLLECTION

We started the VDC Scorecard research with the development of the VDC Scorecard framework and documented this process in Kam et al. (2017). The key point of departure of Kam et al. (2017) was the VDC themes in Kunz and Fischer (2009), which stemmed from the organization that formalized VDC. From these themes, we formulated the Areas and Divisions of the VDC Scorecard framework that should be assessed for a project. Then our framework was compared with previous VDC/BIM assessment frameworks. From the comparison, we found that the previous assessment frameworks were not holistic enough. The previous assessment frameworks were focused on assessing the technology, people, and process, but overlooked the assessment of planning the overall goal of VDC and tracking of the performance of achieving this goal. The previous assessment frameworks were also weak in quantitatively assessing these planning and performance. Another opportunity suggested by the comparison was to make assessment criteria adaptive to the industry norm since VDC is a field that is driven by rapid evolution of technology. Take, for example, the use of parametric modeling, which would have been assessed as an industry best practice in the early 2000s. This today would be assessed as a conventional practice. Given the rapid evolution, the assessment criteria have to be adaptive to the moving industry norms. Hence developing the VDC scorecard framework with the two aforementioned characteristics—a holistic framework and adaptive scoring criteria—was the main goal of our first study (Kam et al. 2017).

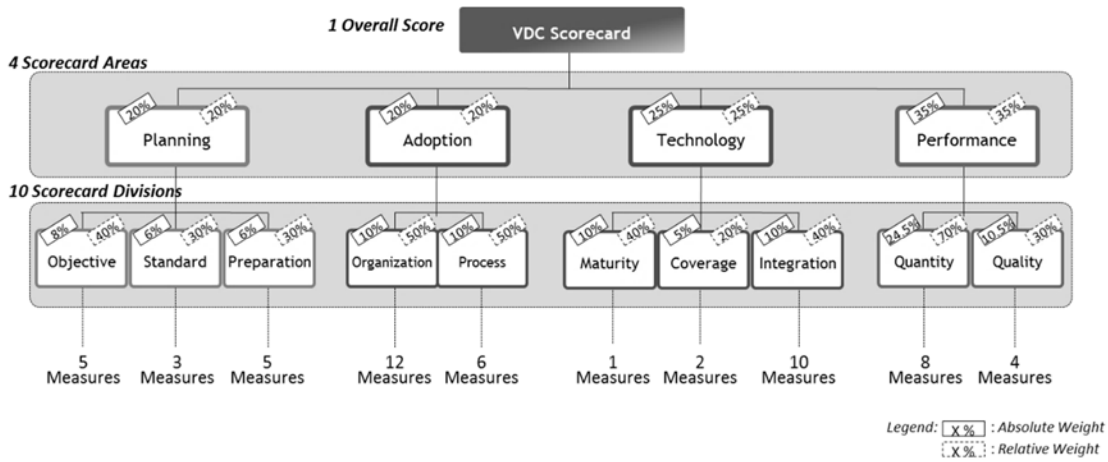

Fig. 1. The VDC Scorecard framework with 4 Scorecard Areas, 10 Scorecard Divisions, and 56 Scorecard Measures.

Fig. 1 shows the resulting framework of the VDC Scorecard in Kam et al. (2017). It has 4 Scorecard Areas, 10 Scorecard Divisions, and 56 Scorecard Measures. The Planning Area in the figure evaluates the establishment of the VDC objectives with quantitative measures. The Adoption Area evaluates the adoption of non-technical, collaborative methods such as integrated concurrent engineering (ICE) (Kunz and Fischer 2009) and integrated project delivery (IPD) (AIA California Council 2007) over the lifecycle of a project. The Technology Area evaluates what prior VDC/BIM assessment frameworks are already covering well—the technical methods for VDC. The Performance Area evaluates the degree to which the VDC objectives established in the Planning Area are achieved, with higher scores given to quantitative rather than to merely qualitative or subjective sentiments. The 4 Scorecard Areas are then branched out into the 10 Scorecard Divisions, and the 10 Scorecard Divisions into the 56 Scorecard Measures. The full list of the Measures is shown in Kam (2013b). The scoring of each Measure is based on percentile and a weighted sum of Measure scores under a certain Division represents the Division score. In the same way, a weighted sum of Division scores represents an Area score, and a weighted sum of Area scores represents an overall VDC score. These weights are indicated in Fig. 1. All the scores are on a scale of 0 to 100. The research presented in this paper uses the VDC Scorecard developed through prior studies (Kam 2013a; Kam et al. 2013, 2017), applies the scorecard to 108 projects, and interprets the data collected with the goal of quantitatively validating the critical factors that support VDC performance.

3. GAP STUDY

The formulation of the VDC Scorecard was designed to give higher scores to a project that critical factors supporting VDC performance than to a project that does not. Our judgment on what critical factors support VDC performance was initially based on the themes of VDC in Kunz and Fischer (2009). Then it was also based on interviews conducted in the course of formulating the VDC Scorecard. Literature review subsequently confirmed the presence of these factors. The first column of Table 1 shows the factors we have identified and the second column shows their appearance in the literature, including our key point of departure, Kunz and Fischer (2009). (Note that in this research, VDC performance is defined as the degree to which VDC objectives are achieved.)

Table 1. Critical factors supporting VDC performance and previous studies addressing the factors.

Factor Supporting VDC Performance	Literature Addressing the Factor	VDC/BIM Assessment Framework	Project-based Observation	Sample Size N > n*	Statistical Analysis**
1. Measurements (e.g., metrics)	Kunz and Fischer (2009)				
	Khanzode (2011)	Δ	O		
	McGraw-Hill Construction (2014b)				
	Sebastian and Berlo (2010)	O			
2.Cross-organizational Sessions (e.g., ICE)	Kunz and Fischer (2009)				
	Khanzode (2011)	Δ	O		
	Homayouni et al. (2010)				
	Molenaar et al. (2014)		O	O	O
	Succar (2009)	O	O	O	
	Sebastian and Berlo (2010)	O			
	Gao (2011)	O	O		
3.Integrative Delivery Approaches	Thomsen et al. (2010)				
	Pishdad and Beliveau (2010)				
	Molenaar et al. (2014)		O	O	O
	Indiana University (2009)	O	O		
	Succar (2009)	O	O	O	
4.Maturity of POP Models	Kunz and Fischer (2009)				
	NIBS (2007)	O	O		
	Indiana University (2009)	O	O		
	Succar (2009)	O	O	O	
	Sebastian and Berlo (2010)	O			
5.Coverage of Product Model	NIBS (2007)	O	O		
	Indiana University (2009)	O	O		
	Succar (2009)	O	O	O	
	Sebastian and Berlo (2010)	O			
	Gao (2011)	O	O		
6.Integration of POP Models	Kunz and Fischer (2009)				
	NIBS (2007)	O	O		
	Succar (2009)	O	O	O	
	Sebastian and Berlo (2010)	O			
	Gao (2011)	O	O		
7.Co-utilization of Technology and Sociology	Kunz and Fischer (2009)				
	Khanzode (2011)	Δ	O		
	Deutsch (2011)				
	Succar (2009)	O	O	O	
	Sebastian and Berlo (2010)	O			
	Gao (2011)	O	O		

Gap

Keys: ICE = Integrated Concurrent Engineering, POP = Product Organization Product, O = Yes, Δ = Partially yes, * = N is the sample size of a study reviewed in the table and n is the sample size of this research, i.e., 108, ** = statistical analysis between factors and VDC performances

Among the 56 Scorecard Measures, we have hypothesized the following critical factors: (1) quantitative measurements, (2) cross-organizational sessions, (3) integrative delivery approaches, (4) maturity of POP models, (5) coverage of product model, (6) integration of POP models, and (7) co-utilization of technology and sociology. Relating these factors to the framework of the VDC Scorecard in Fig. 1, the factors from (1) through (6) are measured in the VDC

Scorecard Divisions, respectively: Objective, Organization, Process, Maturity, Coverage, and Integration. The last factor (7) is related to and measured in both the Technology Area and the Adoption Area.

Most of the literature in the second column of Table 1 pertains to a VDC/BIM assessment framework and acknowledges the importance of the factors by designing them in a framework as measures to be assessed. These VDC/BIM assessment frameworks include the Interactive Capability Maturity Model (I-CMM) in NIBS (2007); the BIM Proficiency Matrix in Indiana University (2009); the BIM Maturity Matrix (BIm3) in Succar (2009); the BIM QuickScan in Sebastian and Berlo (2010); and the characterization framework in Gao (2011). Studies that illustrate such a VDC/BIM assessment framework and incorporate the critical factors in the design of the framework are marked in the third column of Table 1. The fourth column notes that whether or not the studies cover specific project cases in relation to the critical factors.

From the literature review, we have also learned that while there seems to be some consensus on these factors being critical, many of the previous studies are based on qualitative judgment, case studies, interviews, or literature review. In all the studies in Table 1, except for one, the authors' speculations are not validated by a statistical analysis (column 6 in Table 1) based on a mass sample size.

The previous studies in Table 1 shows that among the existing VDC/BIM assessment frameworks, Succar (2009) addresses many of the factors we have identified, captures data in a project-oriented way, and has a large sample size (300+ projects), but the topic that we are interested in—a statistical analysis in regard to the relationship between the factors and VDC performances—is not covered. On the other hand, Molenaar et al. (2014) has a large sample size (204 projects) and conducts statistical analyses but covers only two of the seven factors we have identified. Molenaar et al. (2014) studies the relationship between the factors and project performance, rather than VDC performance[1]; and the overall attention of the study is given to project organization rather than VDC or BIM. In Table 1, the coverage of Succar (2009) and Molenaar et al. (2014) are shaded with gray since they cover our research subjects (the four columns) more than other previous studies. During the formulation of the VDC Scorecard, we collected the VDC scores of 108 projects from 13 countries using the framework in Fig. 1. In this paper, we intend to statistically study the relationships between the factors and VDC performances based on the data collected from these 108 projects to address the gaps found in Table 1.

4. EVIDENCE-BASED UNDERSTANDING OF VDC—HYPOTHESES

The factors that potentially affect the scores of the VDC performance (or the Performance Area) are designed and measured in three Areas of the VDC Scorecard framework: the Planning Area, the Adoption Area, and the Technology Area. We have used the factors in Table 1 to formulate hypotheses H1 through H7 pertaining to a relevant Area in the following ways:

Planning Area:

H1. Measurements support VDC performance: Project members need to define and make public their metrics. Projects with metrics have a higher chance to perform better, because metrics can prompt project members to react when the project appears to veering off course. The hypothesis is supported descriptively by the metrics tied to the three levels of VDC objectives in Kunz and Fischer (2009), by the third controllable factor (metric) in Khanzode (2011), by the responses to the survey question on the importance of metrics in McGraw-Hill Construction (2014a), and by the use of key performance indicators in the assessment framework in Sebastian and Berlo (2010).

Adoption Area:

H2. Cross-organizational sessions (e.g., ICE) support VDC performance: VDC is the use of multidisciplinary models of a construction project. Using multidisciplinary models in cross-organization sessions helps rapid decision making and potentially improves VDC performance. The existing VDC/BIM assessment frameworks that have acknowledged and included this factor are the BIm3 in Succar (2009), the BIM QuickScan in Sebastian and Berlo (2010), and the characterization framework in Gao (2011). In addition to being supported by the VDC/BIM assessment frameworks, the hypothesis is also supported descriptively by ICE in Kunz and Fischer (2009), by the second controllable factor

[1] Performance is the degree to which objectives are achieved. The difference between VDC performance and project performance is that VDC performance relates to the objectives that project members wish to achieve by adopting VDC during the execution of the project (such as conducting weekly 4D simulation, use of location-based scheduling on a field level, etc.) whereas project performance relates to the objectives the project members wish to achieve upon project completion (such as finishing construction within 36 months, etc.).

regarding a multi-disciplinary team in Khanzode (2011), and by the observation on the inter-organizational meeting strategies in Homayouni et al. (2010). Furthermore, the hypothesis is supported explanatorily with the relationship between the inter-organizational team and project performances in Molenaar et al. (2014), although the performance in Molenaar et al. (2014) is project performance, rather than VDC performance as noted before.

H3. Integrative delivery approaches (e.g., IPD) support VDC performance: The use of multidisciplinary models for improving VDC performance can be made early on if multiple stakeholders are brought on board at the beginning of a project. This can be done with an integrative delivery approach. The existing VDC/BIM assessment frameworks that have acknowledged and included this factor are the BIM Proficiency Matrix in Indiana University (2009), and the BIm3 in Succar (2009). In addition to being supported by the VDC/BIM assessment frameworks, the hypothesis is supported descriptively by the use of BIM in an IPD setting for performance improvements in Thomsen et al. (2010) and Pishdad and Beliveau (2010). Furthermore, the hypothesis is also supported explanatorily by the relationship between the project delivery strategies and project performance in Molenaar et al. (2014), although the performance there is again project performance, rather than VDC performance.

Technology Area:

H4. Maturity of POP models supports VDC performance: In the VDC Scorecard research, the maturity of POP models progresses through five levels: 1) visualization, 2) documentation, 3) model-based analysis, 4) integrated analysis, and 5) automation & optimization (Kam 2013b). A core functionality of a modeling application can fall into one of the five levels, and the use of modeling applications that encompass higher levels supports VDC performance. The capability of technology is often assessed by defining multiple levels of maturity—an assessment method attributable to the work of Paulk et al. (1991) in the software industry. Such a maturity model has been adopted to the field of VDC/BIM and to the design of the VDC Scorecard as well. Examples of maturity models, besides ours, in the field of VDC/BIM for assessing technology include the three levels of the VDC maturity model in Kunz and Fischer (2009), the data richness, timeliness/response, and interoperability categories of the I-CMM in NIBS (2007), the content creation and calculation mentality categories of the BIM Proficiency Matrix in Indiana University (2009), the BIM capability stages category of the BIM Maturity Matrix in Succar (2009), and the technology platforms and tools category of the assessment framework in Sebastian and Berlo (2010). Each of these maturity models are designed in multiple levels to acknowledge and credit the adoption of a higher level, which in turn should support VDC performance.

H5. Coverage of product model supports VDC performance: Extending the coverage of the product elements being modeled and planning the progression of the level of development throughout the design, construction and operation stages enrich the information needed for VDC. The existing VDC/BIM assessment frameworks that have acknowledged and included this factor are the I-CMM in NIBS (2007), the BIM Proficiency Matrix in Indiana University (2009), the BIM Maturity Matrix in Succar (2009), the assessment framework in Sebastian and Berlo (2010), and the characterization framework in Gao (2011).

H6. Integration of POP models supports VDC performance: Each designer or contractor brings a certain form of a POP model that they have developed to a project. These individual models ideally should be integrated into a project model without information loss and in a timely fashion to improve overall project VDC performance. The existing VDC/BIM assessment frameworks that have acknowledged and included this factor are the I-CMM in NIBS (2007), the BIM Proficiency Matrix in Indiana University (2009), the BIM Maturity Matrix in Succar (2009), the assessment framework in Sebastian and Berlo (2010), and the characterization framework in Gao (2011).

Adoption Area and Technology Area:

H7. Technical and collaborative methods collectively support VDC performance: In our framework of the Scorecard, the technical methods are captured through the Technology Area, and the collaborative methods are captured through the Adoption Area. The technical methods help improve VDC performance, but successful implementation of technical methods requires collaborative methods, such as ICE, as well. That is, the Technology Area alone does not drive VDC performance but VDC performance is also driven by the collective infusion of the Technology Area and the Adoption Area. Charles Hardy, director of the General Services Administration's (GSA), once noted that BIM is about 10 percent technology and 90 percent sociology (Deutsch 2011). Although this may be an overstatement, other studies also point out the need for balance between technology and sociology for successfully improving VDC performance. The existing VDC/BIM assessment frameworks that have balanced the assessment of technology and sociology are the BIM Maturity Matrix in Succar (2009), the assessment framework in Sebastian and Berlo (2010), and the characterization framework in Gao (2011). In addition to the VDC/BIM assessment frameworks, the hypothesis is supported descriptively by Kunz and Fischer (2009), Khanzode (2011), and Deutsch (2011).

As reviewed above, there is a consensus in our research community on the factors that support VDC performance, but the studies are largely subjective, qualitative, or descriptive. This paper investigates whether the analyses of the data from 108 projects can support the hypotheses we have formulated.

5. METHODOLOGY

In selecting the sample projects, we used judgmental sampling. Projects without BIM usages were not considered. The members of our lab, the Center for Integrated Facility Engineering (CIFE), were the first ones to reach out since many of them were early adopters of BIM, with many of their projects already using BIM. Also to receive a broad spectrum of feedback on the formulation of the questions, multiple facility types and regions were taken into consideration when selecting sample projects. The general intention for a project evaluation was to receive survey input from all project stakeholders. These inputs provide more holistic information on the project from various perspectives. But in reality, all of them were not always accessible. In those cases, the uncertainties in the captured data were reflected in the confidence level. Interviewing was carried out via, phone interview, web-conferencing, email-follow-ups and personal interviews. In over 70% of the projects scored, at least both the architect and the general contractor were interviewed. VDC Scorecard researchers and Students who enrolled in VDC courses carried out the independent interviews, collected the survey inputs, scored, and analyzed the data sets. This paper is based on 108 unique projects.

The variables collected through the Scorecard enable statistical analyses and evidence-based understanding of the critical factors in Section 2. These critical factors were used to set up the hypotheses H1 through H7 in Section 3, in which the subjects of a hypothesis can be represented by a certain Area or Division score. For instance, in the hypothesis "measurements support VDC performance," the score of the Objective Division is representative of "measurements" in the hypothesis, and the score of the Performance Area is representative of "VDC performance" in the hypothesis. Then we carried out correlation tests with the Area scores and Division scores, which are continuous variables. The Pearson, Spearman, and Kendall tests were used to analyze the significance of the correlations between Division-Division scores, Division-Area scores, or Area-Area scores depending on the subjects of a hypothesis. All of H1 through H7 include the term "VDC performance"; hence one variable of a correlation test is always the Performance Area score. The correlation was set to be significant at the 5% level (p-values<0.05). In addition to correlation tests, 108 projects were ranked based on their Overall VDC scores. The top and bottom 25% of the projects were grouped and the average Measure values of the two groups were compared to see whether there are additional meaningful signs of supporting the hypotheses. The findings of this research mainly focus on the hypotheses. However, the research also presents additional findings rendered unintendedly during the statistical analyses but worth sharing.

6. OVERVIEW OF 108 PROJECTS

The projects evaluated using the VDC Scorecard cover 11 facility types. They are distributed across the world in 13 different countries in North America, Europe and Asia. Delivery approaches used by the projects range from conventional ones, such as design-bid-build, to integrative ones, such as IPD and integrated form of agreement (IFoA). They are also evaluated during different project phases from predesign to closeout, and operation and maintenance (O&M). The diversity of the 108 project samples is shown in Table 2. The average Overall VDC score of the 108 projects is 50%, which is exactly the mean of the score distribution. Table 3 shows the number of projects that fell into different tiers of score.

7. ANALYSES OF THE DATA

This section presents the results of the statistical analyses, mainly focused on whether or not the results of the correlation tests support hypothesis H1 through H7. The data presented in this paper are Pearson's Correlation coefficient, but Spearman's and Kendall's statistics gave the same conclusions. In addition to the correlation tests, comparisons were made by grouping, averaging, and counting the values in the data for additional insights.

Table 2. Percentage of projects sorted by facility type, delivery approach, and phase.

Facility Type	% of Project Evaluations
Courthouse	2%
Educational	9%
Entertainment	14%
Healthcare	13%
Industrial	2%
Infrastructure	5%
Laboratory	6%
Mixed-use	5%
Office	19%
Residential	15%
Urban Planning	2%
Other	3%

Project Delivery Type	% of Project Evaluations
Design-Bid-Build	24%
Design-Build	27%
CM at Risk	7%
Integrative	10%
Other	31%

Project Phase	% of Project Evaluations
Predesign	5%
Schematic Design	4%
Design Develop.	10%
Construction Doc.	3%
Construction	46%
Closeout	5%
O&M	28%

Table 3. Score distribution of 108 projects.

Score Tier	Score Range	Overall	Planning	Adoption	Technology	Performance
Innovative	90-100%	0	1	5	1	0
Best	75-90%	5	5	9	6	10
Advanced	50-75%	52	48	61	45	39
Typical	25-50%	49	50	30	44	46
Conventional	00-25%	2	4	3	12	13

7.1. Planning Area

H1 "Measurements support VDC performance": The Scorecard captures the use of metrics through the Objective Division of this Area. The Objective Division suggests 7 categories of VDC objectives (Kam 2013b), and the assessment of this Division is designed to incentivize quantitative measurement—i.e., use of metrics—when establishing and tracking the achievement of objectives. The result (line 1 of Table 4) of the correlation test between the Objective Division and the Performance Area supports H1. We also see that when the correlation is tested between the Objective Division and only the quantitative part of the Performance Area, the correlation (line 2 of Table 4) is higher.

Table 4. Significant correlations (p-values<0.05) between the Planning Divisions and the Performance Areas/Divisions.

Planning Division	Performance Area	Performance Division	Corr	P-value	Line
Objective	Performance		.434	2.64×10^{-6}	1
	Performance	Quantitative	.446	1.32×10^{-6}	2
Preparation	Performance	Qualitative	.264	0.005	3

In addition to the correlation test, the Measure values of the top and bottom 25% (in terms of Overall VDC Score) of the projects were compared. The Measure in this case was for assessing whether or not VDC objectives are quantified for a project. The result is that the top 25% of the projects have 83% of their VDC objectives quantified, whereas the bottom 25% have only 5% quantified. Additionally the average Performance score for projects with quantitative objectives is 60%, whereas that for projects without quantitative objectives is 39%. The analyses show that the projects with a high Overall VDC score tend to show greater concern for quantitative objectives than the projects with a low Overall VDC score. The results collectively support H1.

7.2. Adoption Area

H2 "Cross-organizational sessions support VDC performance": Examples of cross-organizational sessions include ICE, value stream mapping, and meetings for pull scheduling. The Measures of cross-organizational sessions are spread across the two Divisions under the Adoption Area. For instance, the early involvement of stakeholders is measured under the Organization Division, and the efficiency of VDC in an integrated project-wide meeting is measured under the Process Division.

H3 "Integrative delivery approaches support VDC performance": Examples of integrative delivery approaches include IPD, project alliancing, and integrated form of agreement (IFoA). Like the cross-organizational sessions, the Measures of integrative delivery approaches are spread across the two Divisions under the Adoption Area. For instance, the early involvement of stakeholders enables cross-organizational sessions but it also is a characteristic of an integrative delivery approach measured under the Organization Division. Measurements of other characteristics of integrative delivery approaches, such as risk and rewards sharing, can be found in the Process Division.

Hence the Adoption Area is designed to collectively measure the characteristics of the cross-organizational sessions and the integrative delivery approach. The result (Table 5) of the correlation test shows that the correlations between all the Divisions in the Adoption Area and all the Divisions in the Performance Area are significant. This supports H2 and H3.

Table 5. Significant correlations (p-values<0.05) between the Adoption Divisions and the Performance Areas/Divisions.

Adoption Division	Performance Area	Performance Division	Corr	P-value	Line
Process	Performance		.323	0.0006	1
	Performance	Qualitative	.342	0.0002	2
	Performance	Quantitative	.253	0.008	3
Organization	Performance		.242	0.0115	4
	Performance	Qualitative	.301	0.001	5
	Performance	Quantitative	.194	0.043	6

The study on the top and bottom 25% (in terms of Overall VDC Score) of the projects also supported H2 and H3. When we compare the Measure values related to cross-organizational sessions and integrative delivery approaches, the Measure values of the top 25% of the projects outperform those of the bottom 25%. In the top 25% of the projects, 84% of the project organizations use VDC on average, whereas in the bottom 25% only 35% use VDC on average. Furthermore, 100% of the top 25% of the projects had an integrated project-wide meeting involving VDC, whereas only 33% of the bottom 25% had an integrated project-wide meeting involving VDC. The average number of phases covered by a stakeholder is 5.2 for the top 25% of the projects and 4 for the bottom 25% of the projects, which is an indicator of higher stakeholder involvement. Note that the total number of phases is seven (i.e., predesign, schematic design, design development, construction documents, construction, closeout, O&M). These results collectively support H2 and H3.

7.3. Technology Area

H4 "Maturity of POP models supports VDC performance": The Scorecard evaluates the maturity of models with five levels: 1) visualization, 2) documentation, 3) model-based analysis, 4) integrated analysis, and 5) automation & optimization. The result of this evaluation is represented by the Maturity Division score, hence the correlation between the Maturity Division and the Performance Area for H4 is tested. Line 1 of Table 6 shows that the correlation is significant between these two, supporting H4.

H5 "Coverage of product model supports VDC performance": The Scorecard evaluates the coverage of a product model based on the level of development in AIA (2008), which is categorized into 1) Conceptual, 2) Approximate Geometry, 3) Precise Geometry, 4) Fabrication, and 5) As-Built. The result of this evaluation is represented by the Coverage Division score, so the correlation test is done between the Coverage Division and the Performance Area for H5. Line 3 of Table 6 shows that the correlation is significant between these two, supporting H5.

This Area is also where *H6 "Integration of POP models supports VDC performance"* is tested. The integration part of a project is represented by the Integration Division score, which covers information loss during model exchange and stakeholders' accessibility to POP models. Unlike H4 and H5, the result of the correlation test of this Division with the Performance Area is not significant with a p-value of 0.0673. This is greater than 0.05 and hence does not support H6 (only a subpart of the Performance Area, i.e., the Qualitative Division, correlates significantly with the Integration Division). However, since the difference is only marginal, the p-value may easily come under 0.05 with additional sample projects in the future.

Table 6. Significant correlations (p-values<0.05) between the Technology Divisions and the Performance Areas/Divisions.

Technology Division	Performance Area	Performance Division	Corr	P-value	Line
Maturity	Performance		.275	0.004	1
	Performance	Quantitative	.258	0.007	2
Coverage	Performance		.261	0.0063	3
	Performance	Quantitative	.267	0.005	4
Integration	Performance	Qualitative	.226	0.018	5

The study on the top and bottom 25% of the projects was supportive of H4 and H5. We found that more than half of the top 25% have used models in all five levels in the Maturity Division and have used more than one modeling application at each level. This supports H4. The top 25% also tend to model more building elements in 3D—the top 25% have modeled 76% of the building elements, whereas the bottom 25% have modeled only 39% of them (there were 17 building elements surveyed in the Scorecard such as foundation, plumbing, mechanical utilities, etc.). This supports H5. However, integration still seems to be a challenge in the industry as only a few project teams of the top 25% were able to keep low the information loss suffered as a result of a lack of interoperability. This may have affected the weak correlation regarding H6 mentioned above.

7.4. Adoption + Technology

Researchers (NIBS 2007; Indiana University 2009; Succar 2009; Sebastian and Berlo 2010; Gao 2011) and practitioners (Deutsch 2011) emphasize sociology for successful implementing of new technology, which led to our speculation of H7 "Technical and collaborative methods collectively support VDC performance." H7 speculates that a project has to improve both the Technology and Adoption Area scores in order to improve the Performance Area score, and not only one or the other. However, based on our analysis, H7 is yet to be supported by the Scorecard data. For verification, we used a linear model for analyzing a combined effect of two variables: $P = \beta 1 \times A + \beta 2 \times T + \beta 3 \times (A \times T)$, where βs are coefficients, P is the Performance Area score, A is the Adoption Area score, and T is the Technology Area score. In this model, the significance of the combined effect of the Adoption and the Technology is represented by β3. Fitting the data of 108 projects to this linear model, the model came out to be $P = -0.01763 \times A - 0.24777 \times T + 0.73905 \times (A \times T)$. When observing the coefficients of the model, the coefficient of A×T, i.e., β3, is relatively large with the value of 0.73905, which supports H7 that stresses the combined effect of Adoption and Technology. However, the R-squared of the model was low, so the interpretation on this should be reserved until additional data become available and a better model with a higher R-squared evolves from them.

7.5. Fruition in the Performance Area

The Area-level analyses of the correlations show that the correlations between the non-Performance Areas and the Performance Area are weaker than the correlations between one non-Performance Area and another non-Performance Area. Table 7 shows that the correlations between the Planning Area and the Performance Area (line 3), between the Adoption Area and the Performance Area (line 5), and between the Technology Area and the Performance Area (line 6) are all significant. However, it has come to our attention that the correlations among the Planning Area, the Adoption Area, and the Technology Area (line 1, line 2, line 4 shaded with gray) are stronger than those of line 3, line 5, and line 6. Our interpretation of this phenomenon is that the practitioners are investing a great deal of time and effort collectively on the planning, adoption, and technical part of VDC to the point where those three parts correlate strongly, but this strong correlation is not being fully relayed to the performance part (or the Performance Area). The practitioners may be at a stage where several VDC test cases and pilot projects are being deployed without their being sure of the proven ways and proven benefits. That is, the Performance gain is as yet not highly correlated with the initiatives in other Areas.

Table 7. Significant correlations (p-values<0.05) between the Scorecard Areas: Planning, Adoption, Technology, and Performance.

Area		**Correlation**	**P-value**	Line
Planning vs.	Adoption	0.563	2.35×10^{-10}	1
	Technology	0.635	1.58×10^{-13}	2
	Performance	0.393	2.54×10^{-15}	3
Adoption vs.	Technology	0.574	8.54×10^{-11}	4
	Performance	0.361	0.0001	5
Technology vs.	Performance	0.306	0.0012	6

8. CONCLUSION

The authors of this research first collected a set of critical factors that support VDC performances from the study (Kunz and Fischer 2009) done at CIFE where the concept of VDC was originally formalized. Then additional factors were identified in the course of formulating the VDC Scorecard. These factors were checked against the factors observed in the VDC-related studies at CIFE and observed by other researchers. The critical factors we identified were (1) measurements (e.g., metrics), (2) cross-organizational sessions (e.g., ICE), (3) integrative delivery approaches, (4) maturity of POP models, (5) coverage of product model, (6) integration of POP models, and (7) co-utilization of technology and sociology. These factors were then translated into hypotheses H1 through H7. The factors were also incorporated into the design of the VDC Scorecard which allowed us to evaluate the use of the critical factors and

VDC performance of a project. To quantitatively assess whether or not the hypotheses are supported, we used the data collected by the VDC Scorecard designed to measure the use of critical factors and VDC performances. We applied the VDC Scorecard to 108 projects across 13 countries, used correlation tests (Pearson, Spearman, and Kendall), as well as comparative analyses by grouping the data, averaging, and counting. The work presented here shows H1, H2, H3, H4, and H5 are supported by the analyses of the Scorecard data. As for H6 and H7, the analyses do not support them; however, we reserve our judgment on H6 and H7, because the results of the analyses are not contradicting H6 and H7 but are rather in a range that can be seen as support but weak support. One surprising, but valuable, observation made during the analyses was that the correlations between the Planning, Adoption, and Technology Areas were higher than the correlation between any of the three Areas and the Performance Area (Table 7). R^2 also did not exceed 0.4 for any of the three Areas and the Performance Area. This means that the practitioners are investing a great deal of time and effort collectively on the planning, adoption, and technical part of VDC to the point where those three parts correlate strongly, but this strong correlation is not being fully relayed to the performance part (or the Performance Area). We attribute this lower-than-expected correlation between the three Areas and the Performance Area to the inevitable disruption that an industry often has to go through in a transforming stage of innovation and adopting advanced technologies. It is also the goal of the Scorecard team to provide this holistic analysis inclusive of the performance for an individual project, so the investment in VDC planning, adoption, and technology can be tracked and found to pay off in the Performance Area, which VDC ultimately aims to improve.

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Big Data and AI Learning

Data-driven Design for Modular High-rise Residential Buildings Under Wind-induced Ventilation

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ABSTRACT: *In high-rise high-density cities, natural ventilation is a critical issue as it plays an important role for maintaining indoor human comfort, while saving the energy consumption for air-conditioning. Understanding the effect of urban wind on indoor natural ventilation is essential yet challenging for the design of residential high-rise buildings. In this paper, attempts have been made to develop a data-driven design approach for the prediction and optimization of wind-induced ventilation in residential high-rise buildings. The proposed method adopts the modular flat design, coupling deep learning and computational fluid dynamics (CFD) simulation to analyze the ventilation performance for each modular flat in a high-rise building. It involves the CFD simulation to predict the exterior urban airflow and the surface pressure upon various window openings on the building facade. Provided the building surface pressure, multi-zone airflow modelling is performed to analyze the indoor flow rate and natural ventilation efficiency for each modular flat at both the windward and leeward sides. The numerical simulation is carried out to compare the flow characteristics for residential high-rise buildings in various shapes and configurations. The results serve to establish a robust predictive neural network model to forecast and optimize the wind-induced ventilation. A case study, based on the modular housing in Hong Kong, is used to illustrate the workflow of the proposed method and discuss the preliminary results. The findings of this paper provide deeper understandings and interesting insights into the ventilation design of high-rise buildings, which serve as a decision support basis for creating a sustainable built environment.*

KEYWORDS: *complex geometry, design optimization, machine learning, modular construction, natural ventilation, residential high-rise building.*

1. INTRODUCTION

With rapid population growth in urban communities and continuous progress of economic development, constructions of high-rise buildings have reached an unprecedented level in the densely populated metropolises like Hong Kong. The environmental burdens (such as carbon emissions) associated with the building sector are expected to rise as the energy consumption of high-rise buildings are found to be twice of low-rise buildings (Steadman et al., 2017). In Hong Kong, residential and commercial buildings account for 93% of the total electricity consumption in 2016, with a substantial portion caused by the growing demand for air-conditioning to provide thermal comfort for occupants, particularly in the summer season (EMSD, 2018). Wan & Yik (2004) also studied the operational carbon emissions of residential housings in Hong Kong in terms of energy end-use and building characteristics, and it was found that air-conditioning is the primary cause of energy consumption. Since natural ventilation can provide sufficient indoor airflow and reduce the heavy reliance on air-conditioning, research work has emphasized the maximization of wind-induced natural ventilation to reduce the energy consumption for air-conditioning.

Yu & Chow (2001) evaluated the energy use of 20 office buildings in Hong Kong, and revealed that ventilation and air-conditioning maintained by the mechanical system dominate the buildings' carbon emissions. Liu et al. (2015) investigated the geometric relationship on office buildings in China with an average total height of 50 meters. In total, 8 plane shapes were taken into consideration to evaluate the impact of building configuration on energy performance. It was found that linear plane with elongated sides facing north and west was the most energy-efficient in terms of cooling load in the summer season. Liu et al. (2017) conducted an energy assessment on a 75-meter commercial building, taking into consideration the orientation, plane shape, floor area, plane shape factor, floor height, floor number, and window-to-wall ratio. Nowadays, energy simulation has been adopted to streamline repetitive energy modeling processes as it enables fast acquisition of results (Kim & Woo, 2011). Stadel et al. (2011) introduced a conceptual framework that integrates building information model (BIM) and energy simulation tools to quantify operational energy. The comparison between two energy simulation tools, namely Integrated Environmental Solutions' Virtual Environment (IESVE) and AutoDesk Green Building Studio (GBS) was examined. Similarly, other researchers compared traditional energy simulation method (DOE 2.2 simulation engine) and BIM-based simulation method (AutoDesk Revit and eQUEST) for a 6-story building model in New York (Kim & Woo, 2011).

Some research has also evaluated the effect of wind on the natural ventilation and then the energy performance of buildings. The current two major assessment methods for wind environment are Computational Fluid Dynamic (CFD) simulations and wind tunnel tests (Weerasuriya et al., 2018). Asfour & Gadi (2007) employed CFD for predicting airflow rate in buildings. Design parameters such as building geometries, wind directions, and the presence of openings have been considered. Although CFD simulation and wind tunnel tests play a preponderant role in both the academia and industry in that they are accurate, reliable, and well-established, they are computationally very demanding especially if many alternative designs are considered in the optimization. models with different design parameters. Due to the recent boom of machine learning development, neural network emerges as an alternative technique for assessing the aerodynamics in residential buildings. Weerasuriya et al. (2018) proposed an Artificial Neural Network (ANN) to train a surrogated model for pedestrian-level wind environment prediction in both longitudinal and lateral wind speeds. Given its popularity, many researchers have deployed ANN models to predict wind pressure coefficient with different design parameters, including building geometries, dimensions, and wind attack angle, on building shapes (Vrachimi, Melo & Cóstola, 2017), roofs (Chen, Kopp & Surry, 2003), and building surfaces (Bre, Gimenez & Fachinotti, 2018). Yet, possibilities to incorporate neural network in natural ventilation rate prediction – air changes per hour (ACH) – is largely unexplored in the literature. In addition, the residential high-rise buildings constructed nowadays have complex shape and geometry. Understanding the effect of urban wind on indoor natural ventilation of complex-shaped buildings is essential yet lacking, therefore a comprehensive study on the ventilation design of complex-shaped residential high-rise buildings is much needed.

This paper presents an innovative data-driven design optimization method for predicting and enhancing the wind-induced ventilation in residential high-rise buildings. The proposed method couples machine learning and computational fluid dynamics (CFD) simulation to numerically analyze the ventilation performance for high-rise buildings. The results serve as the training data-set to establish a robust deep neural network model for the reliable forecasting and optimization of wind-induced ventilation. A case study is used to illustrate the workflow of the proposed method and to discuss the preliminary results.

2. METHODOLOGY

2.1. Deep neural network (DNN) framework

This section presents the proposed DNN framework for ACH prediction in residential buildings. Information obtained from CFD is used as the data source for machine learning. First, several typical residential building floor plans (including Cruciform-, T-, and Y-shapes) are generated, followed by CFD simulation to determining the airflow rate and ACH for each individual flat unit. Then, the flat arrangement of a building floor plan (such as the position of each flat unit) is described based on several criteria, which are assigned as the input features for DNN. In addition, the ACH values for different flat units are labeled and serve as the output for DNN prediction. Provided abundant labeled data on ACH value for different flat arrangements, an innovative DNN can be employed for natural ventilation rate prediction. After trials of different architectures and parameters, the most promising DNN configurations are applied for the prediction of ACH and evaluation of varying flat arrangements. Following the trained DNN model, alternative flat arrangements can be created and evaluated in order to identify a better ventilation design for maximizing the ACH.

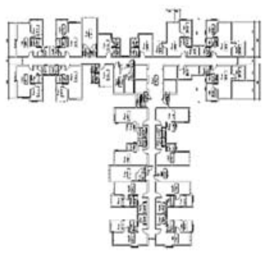
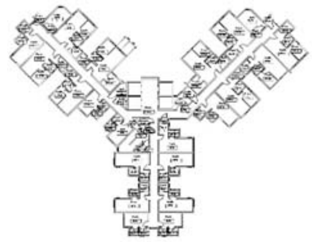
2.2. ACH prediction with DNN

To build the DNN models for regression analysis, a literate programming tool – Jupyter Notebook – is used owing to its readability and popularity in data analysis in recent years (Kery et al., 2018). Tensorflow libraries are used to construct the DNN models. Keras API is adopted to implement the models as it allows users to add and configure layers to the neural network in a sequential order in lieu of defining the entire network at once, facilitating alteration of the number of layers, number of neurons in each layer, the activation functions, and the hyperparameter tuning process (Ketkar, 2017). The training process is implemented on Intel ® Core ™ i5-5200U CPU @ 2.20 GHz, which takes around 10 minutes to finish 500 epochs (forward and backward propagations). The models are computationally inexpensive, and therefore the computation time is omittable.

2.2.1. Dataset

Three sets of data are available, consisting of standard block shapes of public housings. Table 1 summarizes the number of samples, considered wind direction and reference floor level of each plan shape. Each data consisted of its floor plan, wind direction, flat arrangements, and the ACH value of each individual flats obtained from CFD. In total, 457 samples are collected with 153 samples for the Cruciform-shape, 144 samples for the T-shape, and 160 samples for the Y-shape. Two wind directions are considered for each plane shapes: 0° and 45° for cruciform shape; 0° and 180° for T shape; 0° and 180° for Y shape. Four floor levels are chosen: 5th, 15th, 25th, and 35th floor. Each floor level is comprised of four types of flat units: Studio A (14.5 m^2), Studio B (22 m^2), one bedroom (30.9 m^2), and two bedrooms (35.9 m^2). The dataset has the consistent wind environment settings such as the wind velocity and the turbulence intensity, and has been validated by wind tunnel tests, being served as ground truth for this project. Dataset splitting is performed randomly with 70% of the data points assigned for training, 15% of them for cross-validation, and 15 % of them for testing.

Table 1: Summary of training dataset

Plan shape	Cruciform-shape	T-shape	Y-shape
No. of samples	153	144	160
Wind direction	0 and 45	0 and 180	0 and 180
Floor level	5th, 15th, 25th, 35th	5th, 15th, 25th, 35th	5th, 15th, 25th, 35th
Floor plan			

2.2.2. Input features

Since data from CFD give the ACH value for the corresponding flat and the building floor plan, interpretation of these information is required to aid the machine learning process. Flats which do not have an ACH value is first removed. Next, feature selection is performed to convert raw data into information that are suitable for machine learning algorithms. The spatial distribution of each flat is portrayed with reference to its distances and orientation.

Table 2: Summary of input features

Input features	Variable type	Variable
Distance from the core (X1)	Continuous	mm
Orientation w.r.t wind direction (X2)	Continuous	°
Flat size (X3)	Continuous	Studio A (14.5 m^2) Studio B (22 m^2) One bedroom (30.9 m^2) Two bedrooms (35.9 m^2)
Floor height (X4)	Continuous	5th 15th 25th 35th
Flat position – left side (X5)	Discrete	0 or 1 (one-hot encoding)
Flat position – right side (X6)	Discrete	0 or 1 (one-hot encoding)

Input features are decided, with the goal of utilizing the least number of features, yet uniquely describing each flat in a floor. Table 2 summarizes the input features for DNN. From Table 2, a total of six input features are considered for this project, namely (a) distance from the core, (b) orientation with respect to wind direction, (c) flat size, (d) floor height, (e) flat position (left), and (f) flat position (right). These features are selected based on the design variables obtained from parametric modeling to describe the position of the flat units. For the discrete variables, one-hot encoding is implemented for more robust predictions. All the features are converted to tabular data and stored as a comma-separated values (CSV) file format. For example, the flat position input is separated into two columns, one to indicate if the flat is on the left side, and the other if it is positioned on the right side of the wing. The input features are then normalized within the range of 0 to 1 by using the Min-Max Normalization, see Eq. (1). The data preprocessing can avoid the dominance of a particular feature and facilitate the convergence of gradient descent

(Aksoy & Haralick, 2001).

$$X_i^{'} = \frac{X_i - min(X)}{max(X) - min(X)} \tag{2.1}$$

where X_i is the original value and X_i' is the normalized value.

2.2.3. DNN model architecture

The DNN architecture is optimized by exhaustive searching in order to minimize the MSE for better training performance and maximize the R^2 score for prediction accuracy. The model shown in Figure 1 constitutes 4 hidden layers with 50, 80, 80, and 30 neurons for each layer respectively. Hyperparameters such as number of hidden layers, number of neurons in each hidden layer, batch size, learning rate are optimized by exhaustive searching. To mitigate the suppress overfitting, batch normalization is performed before non-linear activation functions in both hidden layers and output layer (Ioffe & Szegedy, 2015). Considering the problem is a multivariate nonlinear regression model fitting, rectified linear unit (ReLU) activation function is selected for the hidden layers and sigmoid activation function is chosen for the output layer to capture the non-linearity. By examining a trial and error process, it is found that a batch size of 15 is the most preferable for the ACH prediction problem. To measure the performance of the DNN models, the Mean Squared Error (MSE) in equation (2) and the R^2 score (coefficient of determination) in equations (3), (4), and (5) are used, as follows:

$$MSE = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \tag{2.2}$$

$$R^2 = 1 - \frac{SS_{Regression}}{SS_{Total}} \tag{2.3}$$

$$SS_{Regression} = \sum_{i=1}^{n}\left(y_i - y_{Regression}\right)^2 \tag{2.4}$$

$$SS_{Total} = \sum_{i=1}^{n}(y_i - \bar{y})^2 \tag{2.5}$$

where n is the number of data points, y_i and $\hat{y}_i$ are the ground-truth value and predicted value respectively; where $SS_{Regression}$ and SS_{Total} is the sum squared regression error and sum squared total error respectively; where $y_{Regression}$ is the regression predicted value respectively; where $\bar{y}$ is the mean value of the whole dataset.

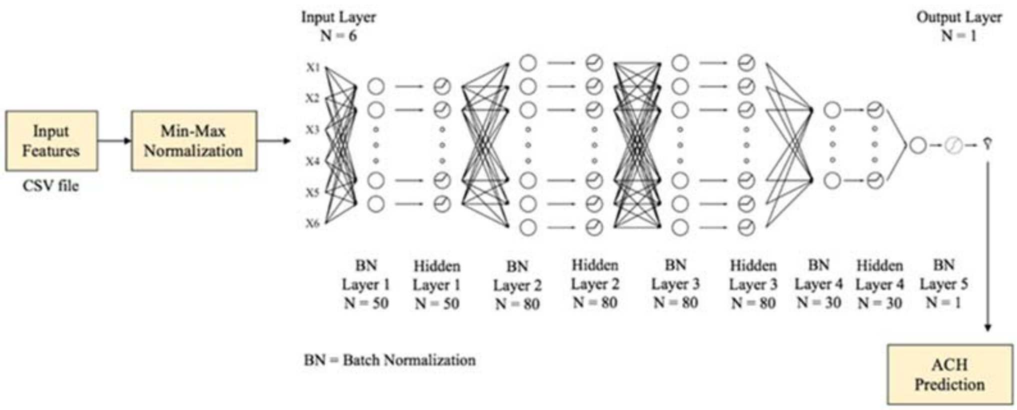


Fig. 1: DNN model architecture

The DNN model applies a scholastic method to fine-tune the optimizer hyperparameter to maximize the DNN models' performance. In total, six commonly used optimizers were investigated, namely Stochastic Gradient Descent (SGD), Root Mean Square Propagation (RMSprop), Adam, Nesterov Adam (Nadam), Adaptive Gradient Algorithm (Adagrad), and Adadelta. Each optimizer has its own characteristic and their default learning rate in Keras libraries. Three separate DNN models (cruciform, T, and Y shapes) and a combined model with all three shapes are evaluated.

3. RESULTS AND DISCUSSION

3.1. Prediction of natural ventilation performance

Figure 2 and Table 3 show the optimizer R2 score and MSE comparisons for Cruciform-, T-, and Y-shapes, respectively. Detailed R2 score and MSE for each individual shapes and a combined scenario with all shapes are discussed below.

Cruciform-shape: According to the simulation results in Figure 2, the RMSprop optimizer with its default learning rate of 0.001 achieved the highest R^2 score of 0.769 and 0.681 for the testing set and the whole dataset respectively. Nadam, Adam, and RMSprop converge to a similar MSE value after 500 epochs; however, RMSprop outperforms the others on the basis of this cruciform shape dataset in terms of the R2 score.

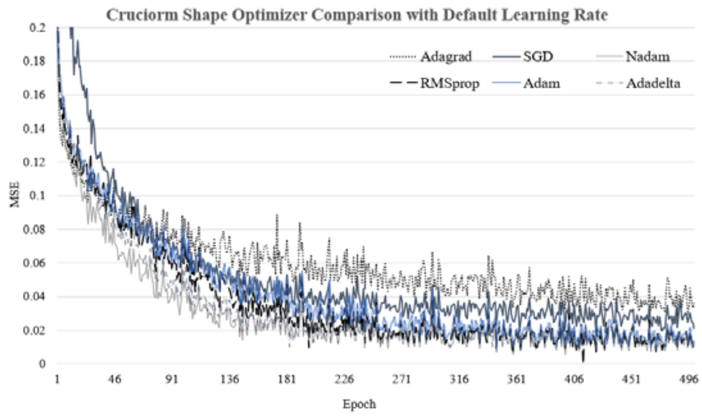


Fig. 2: Optimizer MSE comparison for Cruciform-shape building

T-shape: Based on Figure 3, the Adadelta optimizer with its default learning rate of 0.001 is the best overall choice for the T shape dataset as it attains the highest R^2 score of 0.895 and 0.917 for the testing set and the whole dataset respectively. The high R^2 score in the testing set indicates that this model will not be generalized to the training dataset only, and is able to perform accurate prediction on unseen data. RMSprop, Adam, and Adadelta demonstrate a similar convergence point after 500 epochs; therefore their R^2 scores for the whole dataset are comparable. Adadelta outplays them in terms of unseen data prediction, albeit satisfactory results for the whole dataset.

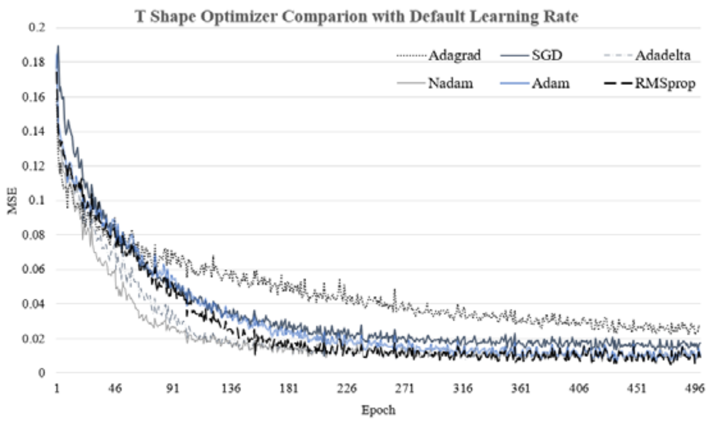


Fig. 3: Optimizer MSE comparison for T-shape building

Y-shape: Similar to the T shape model's result, the Adadelta optimizer scores the highest, with an R^2 score of 0.774 for the testing dataset, and 0.896 for the whole dataset as shown in Figure 4, the learning curve has an identical trend with the T shape model; however, the Adadelta optimizer is comparable to the RMSprop and the Adam optimizer in both testing and whole dataset. Thus, both RMSprop, Adam, and Adadelta are suitable to be applied for the Y shape dataset.

All three shapes: Adam optimizer yields the highest R^2 score of 0.817 and 0.666 for testing and whole dataset respectively. Compared to the previous three models which evaluated each plane shape data independently, this model performs relatively worse in predicting unseen data on the testing dataset in that each building layout has its unique aerodynamic characteristic. To capture all the aerodynamic relationship in the three datasets requires both a more complicated architecture and more dataset to prevent the occurrence of overfitting.

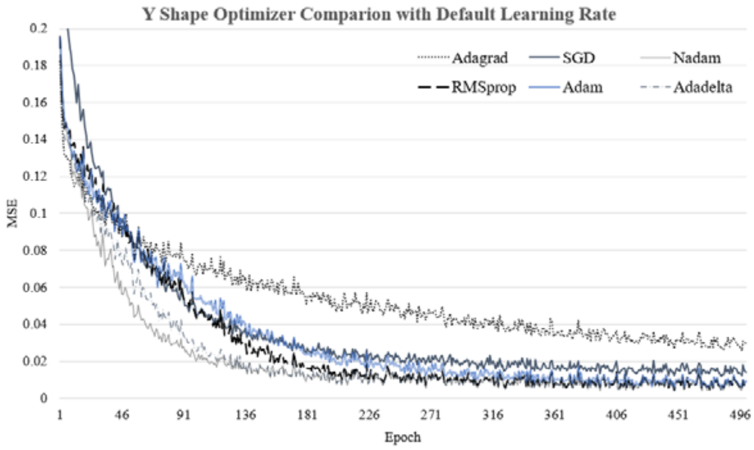


Fig. 4: Optimizer MSE comparison for Y-shape building

As Table 3 shows, RMSprop is the most suitable optimizer for the cruciform shape dataset; Adadelta is recommended for both T and Y shape dataset; Adam has a better performance for all three geometric layouts dataset. Notwithstanding a problem-based black-box model, it can be interpreted that why aforementioned optimizers outperform others such as SGD. These optimizers can be classified into two general types of gradient descent algorithm – constant learning rate algorithm and adaptive learning rate algorithm. SGD is the first type with a constant learning rate throughout the whole training process, and the rest are the second type which updates the learning rate after a specific batch size of epochs. The disadvantage of adopting the constant learning rate is that it is vulnerable to saddle points and could overshoot the global minimum point (Walia, 2017). Within the second type, Adagrad performs the worst compared to other optimizers in that it is particularly adopted in problems with sparse gradient such as natural language and computer vision problems (Palaniappan, 2018). Therefore, it is not suitable for the multivariate non-linear regression problem. As a result, RMSprop, Adadelta, Adam, and Nadam have a better performance in this project.

Table 3: Optimizers comparison

DNN model	Optimizer	Learning rate	Testing set R2	Whole dataset R2
Cruciform shape	RMSprop	0.001	0.681	0.769
T shape	Adadelta	1	0.895	0.917
Y shape	Adadelta	1	0.774	0.896
All three shapes	Adam	0.001	0.666	0.817

3.2. Evaluation of flat arrangements

Subsequent to the development of the neural networks, the DNN models can be implemented fto predict the ACH of each flat for a given floor plan. Different preliminary floor plan designs can be created and evalauted, with the aim of idnetifying the best floor plan with the maximal ACH. The neural network chosen for demonstration is the T-shape model, for the reason of having the highest R^2 score and thus the best prediction accuracy. In addition to the original arrangement for model training, three design schemes were created with one wind direction considered. Figure 5 illustrates the four varying flat arrangements of a T-shaped building plan, categorised according to their flat size. All scenarios consisted of the same number of flats, constituting 3 two-bedroom flats, 8 one-bedroom flats, 4 studio A, and 4 studio B flats, with the areas listed in Table 4.

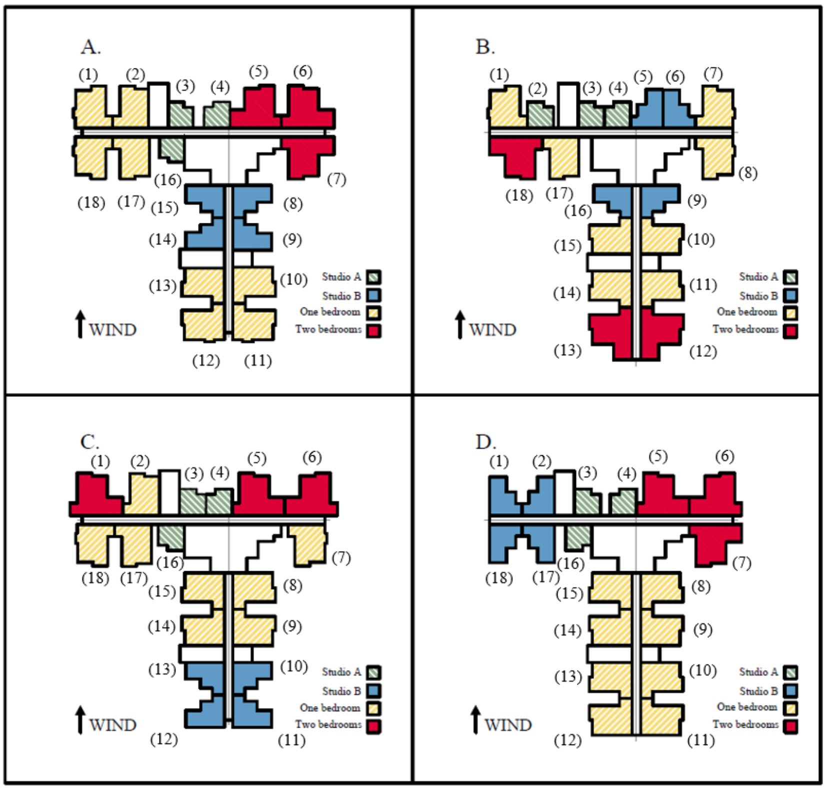


Fig. 5: Flat arrangements for T-shaped floor plan

Table 4: Flat composition for evaluation

Flat Type	Flat Area (m^2)	No. of Flats
Studio A	14.5	3
Studio B	22	4
One bedroom	20.9	8
Two bedrooms	35.9	3

The same number of flat units is retained for all four models, with 3 Studio A flat, 4 Studio B flat, 8 one-bedroom flat, and 3 two-bedroom flat. The flats are organized in a way that the positions of the core and staircases remain the same. The distribution of flats in each design scheme is mainly governed by the positioning of the two larger flat sizes, with: B) two bedroom flats positioned on the windward face and furthest from the core, C) two bedroom flats located on the leeward face only, and D) one bedroom flats positioned at the longest wing and windward face. In views of the better natural ventilation performance for 0° wind direction, the T shape model flat arrangement is based on this particular setting. The objective for different flat arrangements is to maximize the ACH value of the two-bedroom flats in that more occupants require a higher air ventilation rate.

3.3 Performance of Design Schemes

The detailed breakdown on ACH value for each flat unit is provided in Table 5 and Figure 6. The overall objective is to leverage the overall natural ventilation performance for the public housing buildings, without comprising a specific type of flat unit. Therefore, evaluation is based on the following criteria: (1) maximum overall average ACH value; (2) minimal differentiation between the four types of flat units based on the standard deviation.

The highest overall average ACH value is case C, where all two-bedroom flats are placed on the leeward side and all the studio B flats are distributed on the windward side. Notwithstanding the high overall average air ventilation performance, there exists a significant differential distribution between the four types of flat units, the studio B and two-bedroom flat in particular. Likewise, case B provides significant ventilation for two-bedroom flats; however, at the expense of the occupants residing in Studio A, B, and one-bedroom flats.

Table 5: Average ACH value for different flat arrangement

Case	Overall Average ACH	Flat type	Number of flat	Average ACH	Standard Deviation
Case A	16.97	2 bedrooms	3	10.77	4.97
		1 bedroom	8	18.11	
		Studio A	3	11.95	
		Studio B	4	23.11	
Case B	12.56	2 bedrooms	3	34.43	11.55
		1 bedroom	8	7.99	
		Studio A	3	5.68	
		Studio B	4	10.44	
Case C	17.58	2 bedrooms	3	9.21	11.92
		1 bedroom	8	11.06	
		Studio A	3	15.01	
		Studio B	4	38.85	
Case D	15.30	2 bedrooms	3	14.51	4.22
		1 bedroom	8	11.84	
		Studio A	3	14.93	
		Studio B	4	23.12	

For case A and case D, a smaller standard deviation for the ACH distribution between the four types of flats can be found, indicating that these two design schemes are relatively more balanced than case B and case C. However, with a better overall natural ventilation performance for case A, it is more energy-efficient than case D. In addition, the one-bedroom flat in case A, which has the most number of flat units, is more ventilated compared to case C. Therefore, a larger number of occupants are benefited from this arrangement. Concerning the aforementioned evaluation criteria, case A is the preferred one to be adopted.

Besides the comparison between different flat arrangements, two trends regarding the ACH value can be observed in the T shape model with 0° wind direction. Flat units situated on the windward side and further away from the core achieve a better ventilation performance. As such, to maximize a better air ventilation rate, assigning flat units in these positions are suggested. Based on these findings, it is deduced that locating larger-sized flats on the windward side at a distance further from the core is beneficial with respect to the air change rate, and consequently the natural ventilation.

For the assessment of which design schemes are more desirable than the other, the average ACH value for the whole floor is first calculated. From this perspective alone, Scheme C showed the highest overall ACH of 17.58; with Scheme A following close with 16.97 ACH. However, when calculating the average ACH for each flat type, Scheme C showed a wide distribution of the value amongst them, with Studio B having an ACH of 38.85, more than four times of the value obtained by the two bedroom flats. Contrastingly for Scheme A, though second in the average ACH for the floor, did not show such unbalanced distribution of air change rate. Thus, with regard to the distribution of ACH, though Scheme C yield the highest overall value, Scheme A prevailed over C

4. CONCLUSIONS AND RECOMMDATIONS

This study aims to develop a innovative DNN model for evaluation and optimization of wind-induced natural ventilation in residential high-rise buildings. The optimization models of ACH for three typical complex-shaped residential buildings are developed in this study. The T-shaped model is implemented to evaluate different alternative flat arrangements and to idnetify the optimum arragement, with the aim of maximizing the overall ACH for the entire floor. There is still room for future improvement of the DNN models, by first fine-tuning the other hyperparameters such as momentum. In addition, if more training dataset are available, a deeper and wider DNN network can be established to capture the non-linearity of the ACH prediction problem. It is also recommended to evaluate other geometric layouts such as cruciform and Y-shape with a better DNN model for these datasets.

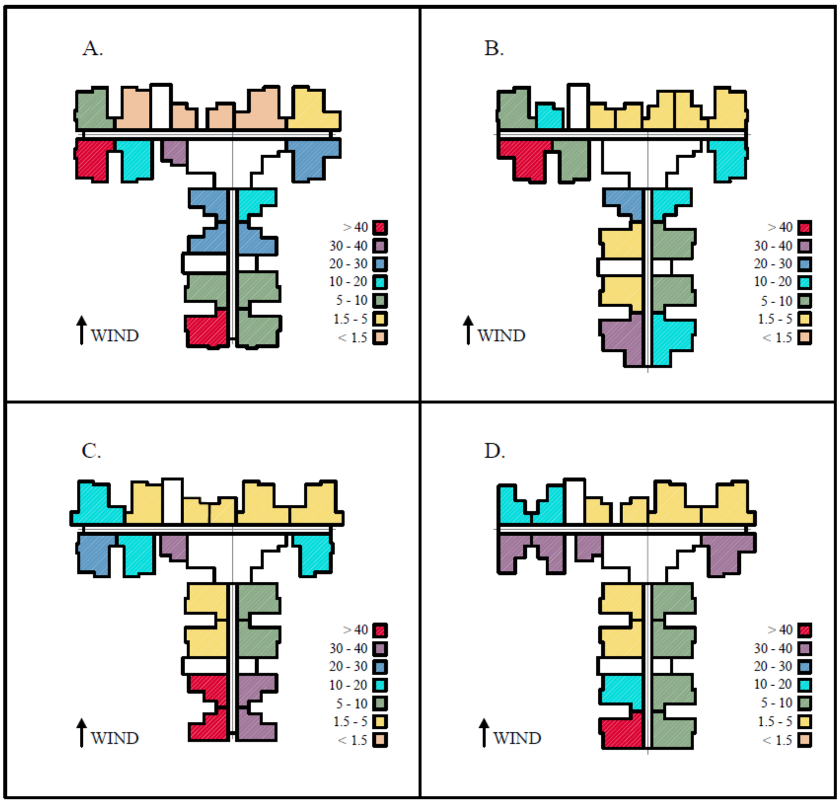


Fig. 6: ACH values for T shape model flat arrangements

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LSTM based advance rate predictive model when shield tunneling in mixed ground condition

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ABSTRACT: *The advance rate (AR) is one of the most significant parameters in shield tunneling construction, which has a dominant impact on construction efficiency. While tunneling in mixed ground condition, it seems difficult to understand the time-varying laws of instantaneous AR, as most current researches focus on the average values per ring of shield tunneling parameters and the presented approaches neglect the influences of history operations. From a practical perspective, it's therefore beneficial to have a model capable of predicting the AR with the consideration of instantaneous parameters and history operations. In this study, a long short-term memory (LSTM) recurrent neural network model is presented with the slurry shield tunneling in the mixed ground of round gravel and mudstone in Nanning metro, and the model performances in different ground conditions are investigated. The results show that the LSTM model can be effectively implemented for the AR prediction, whose overall root mean square error (RMSE) is 2.57 mm/min. A high correlation is observed between predicted and measured AR with the correlation coefficient (R2) of 0.93 in the test set. Moreover, the LSTM based AR predictive model is compared with the random forest (RF) model, the deep feedforward network (DFN) model and the support vector regression (SVR) model, which shows the LSTM model has the best performance with the smallest RMSE value and largest R2 value.*

KEYWORDS: *shield tunneling；advance rate prediction；long-short term memory；deep learning.*

1. INTRODUCTION

Owing to the growing demand for efficient inter/intra-city transportation in China, shield tunneling in mixed ground condition has become increasingly universal nowadays(Xie *et al.*, 2017; Huang *et al.*, 2019). It's crucial to maintain the advance rate (AR) at a reasonable level during the shield tunneling construction in order to ensure the construction safety, control the shield attitude and improve the tunneling efficiency, especially in mixed ground condition. However, the complex geological conditions in the mixed ground have brought great difficulties in shield tunneling control, which may trigger severe consequences, such as instability in the excavation face(Zhao, Gong and Eisensten, 2007), and high cutter wear(Küpferle *et al.*, 2018). Pursuit to better tunneling control means the engineers need to have sufficient understanding about the time-varying laws of the instantaneous shield tunneling parameters. Therefore, it's beneficial to establish an AR predictive model so as to achieve an optimized operation condition.

As a data-driven method, machine learning (ML) based approaches have been carried out in the AR prediction both including the earth pressure balanced (EPB) shield tunneling, the slurry pressured balanced (SPB) shield tunneling, and hard rock tunneling boring machine (TBM). Benardos and Kaliampakos (Benardos and Kaliampakos, 2004) employed the artificial neural network (ANN) to predict the hard rock TBM AR in the Athens metro tunnel, whose model only considered the rock properties as the input but ignoring the operation parameters. Yagiz and other researchers employed ANN(Yagiz *et al.*, 2009; Armaghani *et al.*, 2017), extreme learning machine (ELM) (Shao, Li and Su, 2013), and support vector regression (SVR) (Mahdevari *et al.*, 2014) to predict the penetration rate (AR/Rotation speed of cutter head) using data set from Queens Water Tunnel. Sun et al (Sun *et al.*, 2018) proposed a random forest AR predictive model in the mixed ground condition containing clay, sand, and rock. It sounds reasonable that their model employed the instantaneous values of shield tunneling parameters. However, the predictive model for AR only achieved an R2 value of 0.803 in the test set.

Although great achievements have been made in the area of ML-based advance rate predictive methods for tunneling parameters, there are still limitations: on the one hand, data used for training and test in the ML model is quite limited, which is usually averaged over one ring's (EPB and SPB) or several cycles (hard rock TBM) in tunneling history. On the other hand, the temporal effect is rarely considered and only one-step-back's data is taken into consideration in the ML model, especially for the EPB and SPB. As a spermatic machine, hundreds of sensors on the shield record the shield-soil interactive responses via the programmable logic controller (PLC) every 1~10 seconds, and these instantaneous values (PLC data for short) are the foundation for on-site operators to control the tunneling process.

Thus, we hold the idea that it's more meaningful to establish the AR predictive model with instantaneous value as well as to consider a longer history operation effect. When we consider the instantaneous values of shield tunneling parameters, one big challenge is to deal with such massive data, which seems difficult for the traditional ML methods (e.g. ANN with two or three layers, SVR) to realize our goal. Therefore, deep learning (DL) based methods are the first choice for predicting the instantaneous AR. Among the DL based methods, the long short-term memory (LSTM) recurrent neural network (RNN) has the ability to take the temporal effect into account, which is often be employed in the time series prediction. Gao et al (Gao *et al.*, 2019) proposed an RNN (including LSTM) model to predict the shield tunneling parameters including the cutter head torque, total thrust, and advance rate, which outperforms than traditional ML regression methods (such as SVR, RF, and Lasso) in most cases. However, only 3000 samples from a tunnel section in Shenzhen metro, which didn't show the feasibility of RNN (including LSTM) in dealing with the huge data set of instantaneous shield tunneling parameters. Thus, we are convinced that it's beneficial to adopt deep learning-based LSTM neural network for the advance rate prediction.

This study aims to present an AR predictive model for shield tunneling construction, and to evaluate the model performance compared with other ML based models. In the rest of this paper, we firstly describe the proposed LSTM based AR predictive model, then the modeling process and prediction results, which will emphasize the model in different ground conditions, after which the results and discussions about the performances of different models are detailed. Finally, the conclusions are drawn in the last section.

2. LSTM BASED PREDICTIVE MODEL FOR AR

The AR predictive model can be described as follows: given the PLC data at time *t*-1 $\mathbf{X}_{t-1} = (X_{t-1}^{(1)}, X_{t-1}^{(2)}, \ldots, X_{t-1}^{(m)})$, where *m* means the types of input PLC data, e.g. total thrust but without AR, let $\mathbf{Y}_t$ be the AR at time *t*, it is expected to establish a predictor *F* to realize the function of approximating the actual output $\mathbf{Y}_t$ accurately, as demonstrated in Eq.(2.1).

$$\mathbf{Y}_t = F(\mathbf{X}_{t-1}, \mathbf{X}_{t-2,} \mathbf{X}_{t-3,} \ldots \mathbf{X}_{t-n}) \tag{2.1}$$

Here a time window with width *n* is employed due to the following two reasons: one is the spatial distribution of sensors in the shield, which makes the AR at time *t* is influenced by the historical PLC data. The other one is the complicated shield-soil interaction, e.g. the slurry infiltration and filter cake formation (Min, Zhu and Han, 2013), similar to the natural language process (NLP), which makes the previous operation will have an influence on the current AR. Hence, the AR predictive model is supposed to have the ability to take historical inputs into consideration. According to the plentiful applications of LSTM in the area of the NLP, we are convinced that the LSTM based neural network is suitable for the AR prediction.

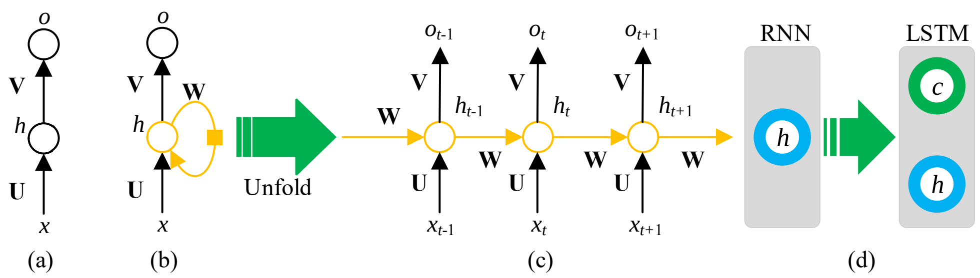


Fig. 1 (a) Feedforward network, (b) recurrent neural network (RNN), (c) RNN unfolding in time, and hidden layer comparison between RNN and LSTM. *x, s,* and *o* are the input layer, the hidden layer, and output layer respectively while **U**, **W**, and **V** represent their weight matrixes.

Fig. 1 shows the typical architectures of feedforward network and recurrent neural network (RNN), and the major difference between RNN and feedforward network is the feedback in the hidden layers of RNN(LeCun, Bengio and Hinton, 2015). If we unfold the RNN in the time dimension, the architecture will turn to be the one illustrated in Fig. (c). It's clear that the output o_t at time *t* is not only affected by the current input x_t, but also the previous hidden layer h_{t-1} That's the reason that RNN can have a 'memory' of the historical inputs. However, while easy to implement the forward pass calculation, it's such difficult to conduct the backpropagation during the training of RNN due to the gradient vanishing problem(Sutskever, 2013). Therefore, the LSTM neural network (Hochreiter and Urgen Schmidhuber, 1997; Gers, Schmidhuber and Cummins, 2000) is put forward whose hidden layer has an additional cell state, *c*, as illustrated in Fig. (d).

The forward pass calculation of LSTM hidden layer is realized with three gate layers, namely, the forget gate, the input gate, and the output gate, respectively, as illustrated in. The gate layer is a kind of feedforward network with one hidden layer, whose output is a real number between 0 to 1 to decide which information to remember or to forget.

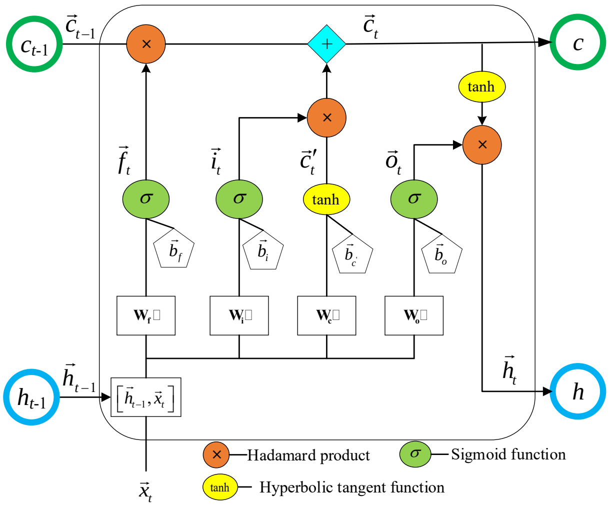


Fig. 2 Forward pass calculation of LSTM hidden layer

The detailed calculation in can be expressed by Eq.2.2. In these equations, $\vec{f}_t$, $\vec{i}_t$ and $\vec{o}_t$ represent the output vectors of three kinds of gates, the forget gate, the input gate, and the output gate, respectively. $\mathbf{W}$ and $\vec{b}$ are their corresponding weight matrixes and bias value vectors. $\vec{c}'_t$ is the candidate cell state vector at time *t*. $[\vec{h}_{t-1}, \vec{x}_t]$ is a new vector that connected by output vector $\vec{h}_{t-1}$ at time *t*-1 and input vector $\vec{x}_t$ at time *t*. σ and $\tanh$ are sigmoid and hyperbolic tangent activation functions. □ is the Hadamard product operator. $\vec{c}_t$ is the cell state at time *t* and $\vec{h}_t$ is the hidden layer output at time *t*. The forget gate $\vec{f}_t$ is used to decide what information is going to be thrown away from the previous cell state $\vec{c}_{t-1}$. The input gate $\vec{i}_t$ and candidate cell state $\vec{c}'_t$ are adopted to determine what new information to be stored in the current cell state $\vec{c}_t$. The output layer $\vec{o}_t$ is employed to generate the current hidden layer output $\vec{h}_t$. The training of the LSTM neural network can be realized with the algorithm of back-propagation through time (BPTT) (Hochreiter and Urgen Schmidhuber, 1997; Gers, Schmidhuber and Cummins, 2000).

$$\vec{f}_t = \sigma(\mathbf{W_f} \cdot [\vec{h}_{t-1}, \vec{x}_t] + \vec{b}_f) \tag{2.2}$$

$$\vec{i}_t = \sigma(\mathbf{W_i} \cdot [\vec{h}_{t-1}, \vec{x}_t] + \vec{b}_i) \tag{2.3}$$

$$\vec{c}'_t = \tanh(\mathbf{W_c} \cdot [\vec{h}_{t-1}, \vec{x}_t] + \vec{b}_{c'}) \tag{2.4}$$

$$\vec{c}_t = \vec{f}_t \odot \vec{c}_{t-1} + \vec{i}_t \odot \vec{c}'_t \tag{2.5}$$

$$\vec{h}_t = \vec{o}_t \odot \tanh(\vec{c}_t) \tag{2.6}$$

3. CASE STUDY IN NANNING METRO

3.1. Data description

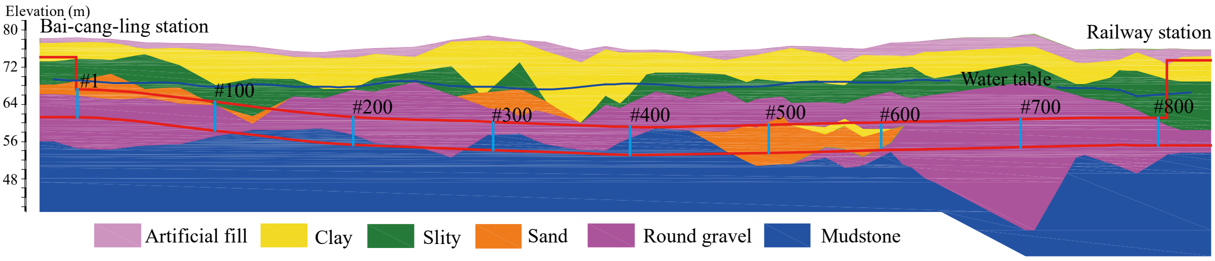


Fig. 3 Cross-section view of BR section in Nanning metro line 1. # 100 means ring # 100 in the left line

The tunnel studied in this study is located in Nanning metro line 1, a southwest city in China. The left line in the section of Bai-cang-ling station to Railway station (BR section) is proposed, and there are a total of 806 rings with the ring width of 1.5 m. Fig. 4 demonstrates the soil distribution along the tunnel alignment. We can see that the round gravel and mudstone are the most frequently encountered soil. According to the geological survey report, there are about 524 rings (65% of total rings) fully located in the round gravel, and 282 rings (35% of total rings) located in the mixed ground condition of round gravel, mudstone, and sand. It can be told from Fig. 4 that the mudstone area is around ring # 120 to ring # 220, and ring # 283 to ring # 470. The tunnel was excavated with an SPB shield machine manufactured by Herrenknecht, whose diameter is 6.28 m.

The AR in the mixed ground has higher fluctuations than in the mudstone and round gravel. To meet the prediction requirements in mixed ground condition, the AR predictive model should capture these patterns. Based on existing research (Xie *et al.*, 2017; Sun *et al.*, 2018) and field experience, the PLC data of slurry pressure in the excavation chamber (SPE), slurry pressure in the working chamber (SPW), the cutter head torque, total thrust, rotation speed, pump pressure of thrust cylinders, and flow rate in feed and return line will be takend as the inputs paramters in the AR predictive model. Therefore, Fig.4 shows the time series of the above mentioned PLC data in the mixed ground. Obviously, clogging occurred in ring # 175 due to the strong fluctuation of SPE, and such fluctuations are observed in the time series of torque, total thrust, and slurry flow rate in return line. The thrust cylinders are grouped in A, B, C, and D in the clockwise. The pump pressure of thrust cylinders in group C is always larger than that in group A indicates that the operators tried to prevent the shield knocking head in the mixed ground.

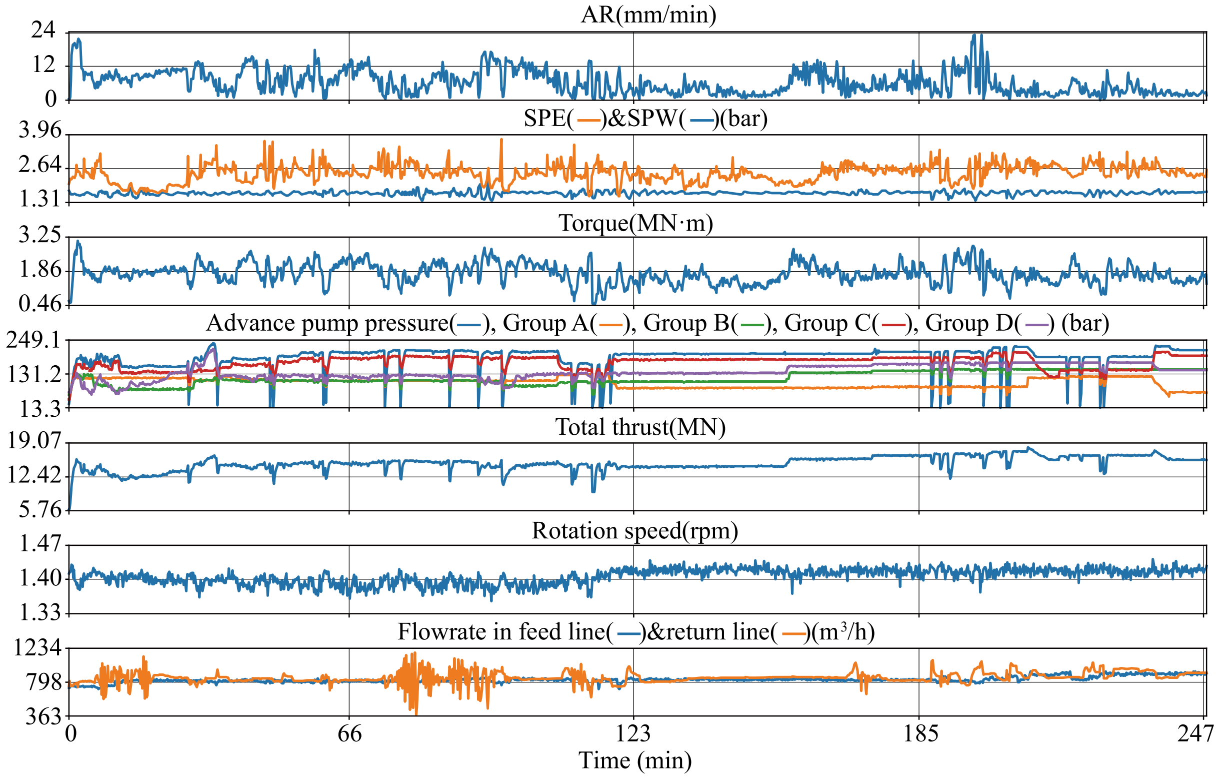


Fig. 4 PLC data related to AR of ring # 175 in mixed ground

3.2. Modeling process with LSTM

In the project for demonstration, there are 665 complete rings with a sequence length of 411,404 are selected from the left line in BR section, which is divided into the training set, the validation set and the test set with the ratio of 0.8:0.1:0.1. The 12 kinds of PLC data are regarded as input parameters, as shown in Fig.4. When the time-series data has been transferred to the supervised learning data, the 0-1 normalization is performed to eliminate the units of measurement for PLC data from different sensors, as illustrated in Eq.(2.7).

$$X_{new} = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \tag{2.7}$$

Fig. 5 demonstrates the proposed LSTM based predictive model for AR in the mixed ground. In this study, we employ

5 minutes of historical operation in the input layer, which means the time steps is 30 as the PLC system stored the data every 10s. The input PLC data fed to the LSTM layer is a 3D tensor. There are 192 neurons in LSTM layer that is determined by the numerical experiments. After the LSTM layer, a dropout layer is conducted to prevent overfitting problem(Srivastava *et al.*, 2014). The key idea of dropout is to drop some neurons (set the output to zero) randomly during the training process with some probability, which is helpful for preventing complex co-adaptations on the training data. According to the experience, the dropout ratio adopted here is 0.2. Then we stack two fully connected layers with different neurons (dense layers in Keras) after the dropout layer, which is beneficial to extract more features and transit features from high dimensions to low dimensions. At last, a dense layer with one neuron performed as the output layer is presented. The activation functions used in the dense layers are all Relu function. The bath size we employed here is 256 with the loss function of mean square error (MSE). Moreover, the correlation coefficient (R^2) is regarded as the metrics to evaluate the predictive model performance. During the training process, the Nadam optimization method with the learning rate of 2×10^{-3} and the decay value of 4×10^{-3} is employed.

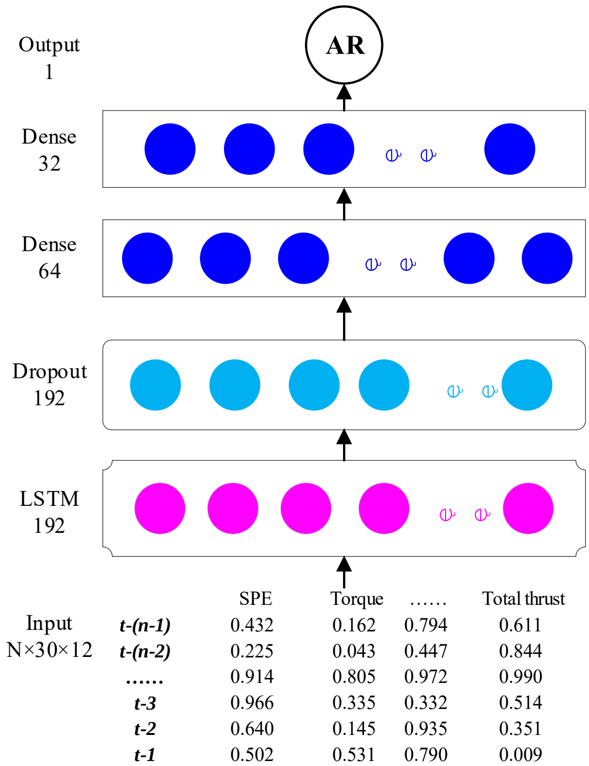
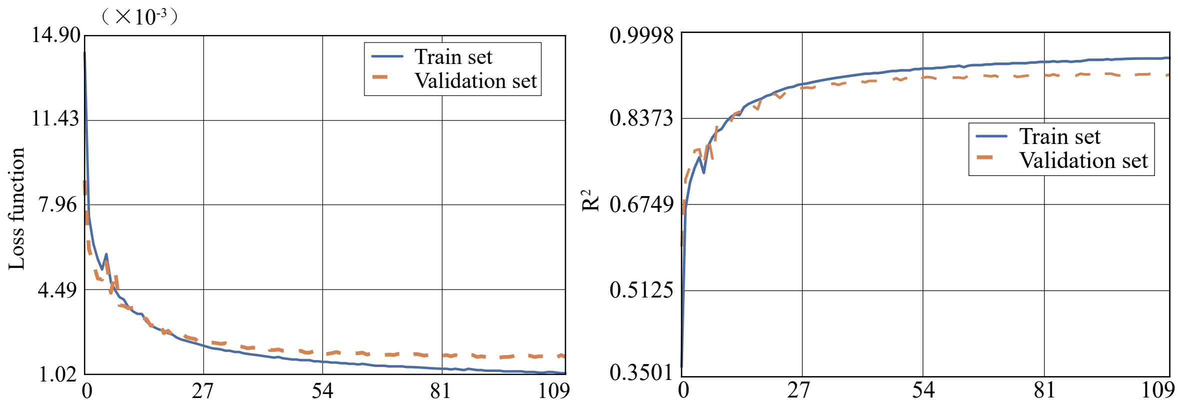


Fig. 5 LSTM predictive model structure, integers like 192 and 64 are the nodes in each layer



(a) Variations of loss function (b) Variations of R^2 values

Fig. 6 Variations of metrics in training and validation set during the training process of the proposed model

With 109 epochs training, the variations curves of the loss function and R^2 values are demonstrated inFig. 6 . The early-stop technology here is conducted for preventing overfitting via motoring the loss function of the validation set with the following criterion: if the loss function value doesn't decrease after 10 epochs (patience), the training process will stop and the current model will be taken as the final model. As can be seen from Fig. 6 (a), when the epochs are larger than 100, the validation loss remains unchanged while the training loss is still decreasing, thus we believe it's necessary to stop training so as to preventing overfitting problem. As illustrated in Fig. 6 (b), the R^2 values increased as the training epochs increased, and at last the proposed model achieved R^2 value in the test set of 0.9312.

3.3. Results of AR prediction

Here we define the ΔAR as $\Delta AR = AR_{measured} - AR_{predicted}$, and the absolute value of ΔAR is shown in Fig. 7. Although the overall root mean square error (RMSE) of the proposed model is 2.57 mm/min, there are several extreme values of ΔAR that is up to 20 mm/min. Meanwhile, by comparing with the mudstone thickness distribution, it' found that in the mudstone rich area, the ΔAR seems smaller than in the round gravel area. Therefore, three rings in typical ground conditions are selected to investigate the details of predicted AR, which are the ring # 175 (the mixed ground), ring # 420 (the mudstone ground), and ring # 680 (the round gravel ground).

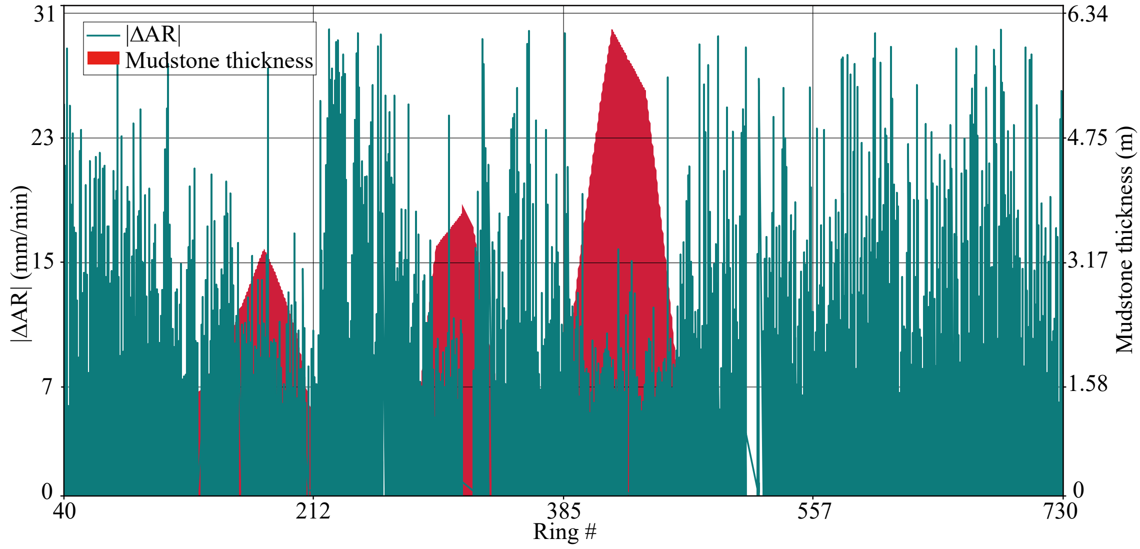


Fig. 7 Absolute value of ΔAR and the distribution of mudstone thickness in tunnel face

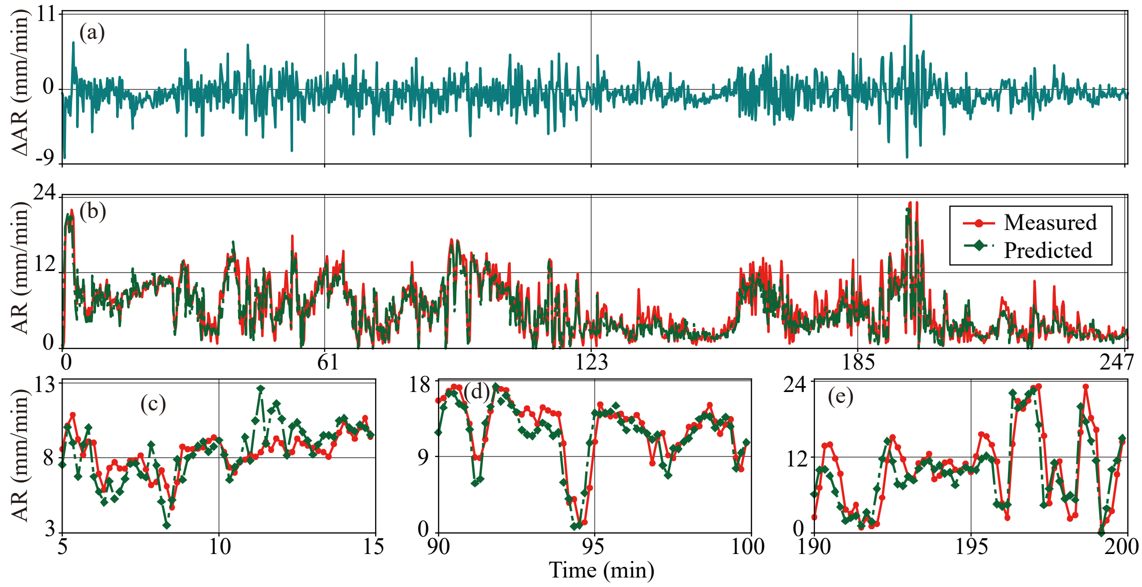


Fig. 8 ΔAR and variations of measured and predicted AR in ring # 175, the mixed ground condition with RMSE of 1.90 mm/min

The first selected ring (ring # 175) is located in the mixed ground, as illustrated in Fig. 9. The values of ΔAR are distributed between -9 mm/min to 11 mm/min, and the RMSE value of 1.90 mm/min indicates that the predicted AR is very close to the measured AR. As mentioned in section 2.2, the clogging has resulted in various change models of AR. However, the proposed LSTM based predictive model is able to capture these change models, as detailed in Fig. 8 (c), (d), and (e). We can see that in most cases, the predictive model has captured the patterns and only some values are wrong estimated, which leads to the errors of the predictive model.

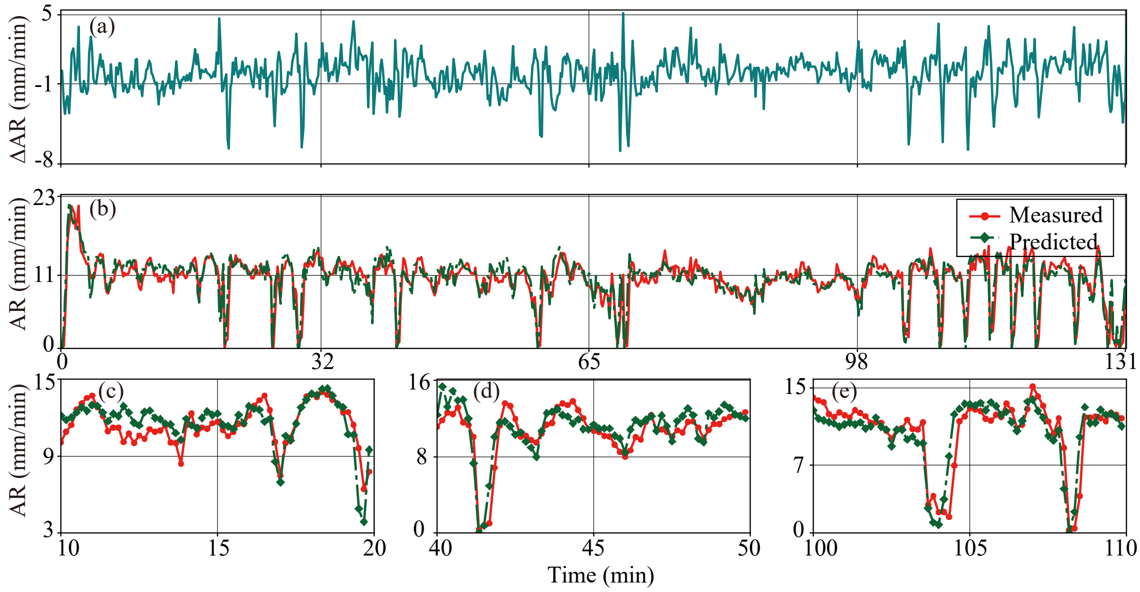


Fig. 9 ΔAR and variations of measured and predicted AR in ring # 420, the mudstone ground condition with RMSE of 1.60 mm/min

Then it's ring # 420 in the mudstone ground shown in Fig. 9. It's found that values of ΔAR are distributed among 5 mm/min to -8 mm/min, as shown in Fig. 9(a). A special pattern observed in Fig. 9 (b) is that there are frequent stop-start operations. The proposed model has done well in predicting the AR from around 11 mm/min to zero, and then from zero to around 11 mm/min. The good estimation of the stop-start pattern makes the RMSE smallest among these three rings.

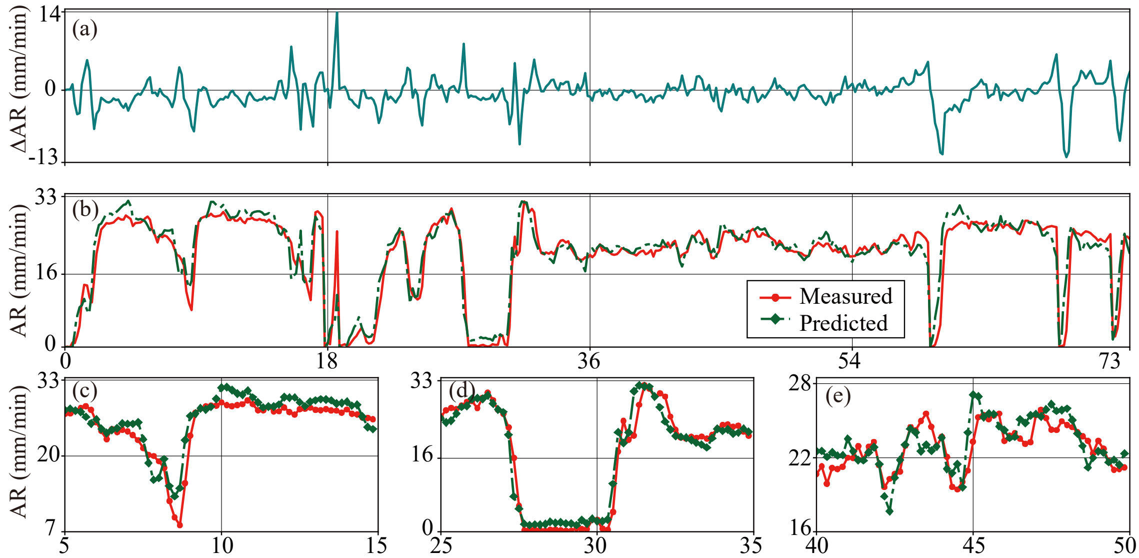


Fig. 10 ΔAR and variations of measured and predicted AR in ring # 680, the round gravel ground condition with RMSE of 2.67 mm/min

The last one is ring # 680 from the round gravel ground, as illustrated in Fig. 10. The values of ΔAR ranges from 14 mm/min to -13 mm/min are observed in Fig. 10 (a). Though the variation tendency has been captured by the proposed model in this ring, the model prefers to estimate higher or lower AR at the peak values (Fig. 10. (b), (c), and (e)), which has brought about an RMSE value of 2.67 mm/min, the largest one among these rings.

3.4. Comparisons with RF, DFN and SVR predictive models

In order to verify the proposed LSTM based predictive model performance, three predictive models including the RF model, the deep feedforward network (DFN) model, and the SVR model are employed to see the model performances in predicting AR. The same data set is used with 5-fold cross-validation. The maximum of tree depth in the RF model is 20 with the n_estimators of 100. The DFN model has the similar structures with the LSTM model, which consists of one input layer with 128 neurons, two hidden layers with 64 neurons and 32 neurons, respectively, and one output layer with one neuron. All the activations functions used in the DFN model are Relu function, while the batch size is 256, and other parameters are the same with the proposed LSTM based model. The RBF function is adopted as the kernel function of the SVR model, which has a scale of 2.5574, a C value of 0.1829, and a bias of 0.1031. The ε value of the SVR model is 0.0183.

Table shows the R^2 values in the test set and the overall RMSE values. The proposed LSTM based model performs best both in the metrics of R^2 values and the overall RMSE values among these four predictive models. The RF model performs a little worse than the proposed LSTM based model but the overfitting problem is the worst as the RF model achieves a high R^2 value of 0.9395 in the training set. The SVR model achieves the lowest R^2 value and the highest RMSE value, which seems unsuitable for prediction the instantaneous AR.

Table 1 R^2 and RMSE values of different predictive models

Metrics&Models	LSTM	RF	DFN	SVR
R^2	0.9312	0.8890	0.8725	0.8360
RMSE (mm/min)	2.57	3.14	3.90	4.24

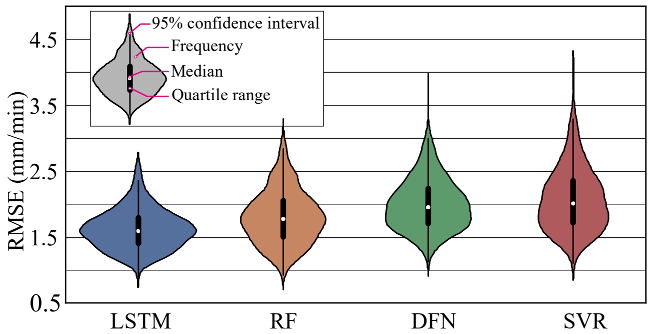


Fig. 11 RMSE values comparison among these four models

To evaluate the predicted errors of these models in details, we carry out the violin plots- a hybrid of box plots and kernel density plots- in Fig. 11. The white dot in the middle of each violin means the median value of RMSE and we can see that the LSTM model has the smallest ones. The thick black bar in the center represents the interquartile range, and the LSTM model is the smallest as well. The thin black line extended from the thick black bar represents the upper (max) and lower (min) adjacent values in the RMSE with a 95% confidence interval. The width of the violin is the density plot rotated and placed on each side, to show the distribution shape of the RMSE values. We can see that the RMSE values obtained by the LSTM model are mostly distributed between 1 mm/min to 2 mm/min, while the other methods have the distributions between 1 mm/min to 3.5 mm/min.

The reason that the proposed LSTM model performs better than the other methods can be explained by the following two aspects: Firstly, from the perspective of the physical mechanics mechanism affecting the shield AR during the tunneling process, the interaction mechanism between the slurry and the soil is complicated, which leads to a hysteresis effect between the cutter head and the soil on the excavation face. As a result, the current AR is affected by other PLC tunneling parameters measured at the historical time. Secondly, from the data view, the input parameters of the LSTM model are 3D tensors, while the RF model, the DFN model, and the SVR model are only 2D matrices. From a data-driven perspective, the 3D tensor implies higher characteristics than the 2D matrices, so the LSTM model can learn the features needed from a higher feature space. Combining the above two factors, in the case shown in this study, the proposed LSTM model performs better than the other models.

4. CONCLUSIONS

In this study, an LSTM based AR predictive model for shield tunneling construction has been developed, which has realized the prediction of AR in the mixed ground in Nanning metro with the overall RMSE value of 2.57 mm/min. The model performances in different ground conditions are evaluated in details, as well as the model comparisons are conducted. The following conclusions can be drawn:

(1) The LSTM based predictive model has the ability to considering the influence of the historical operations on the AR. The AR of SPB shield tunneling in the mixed ground condition of the round gravel and mudstone is easy to have great fluctuations, which can be captured by the LSTM model with the R^2 value of 0.9312 and RMSE value of 2.57 mm/min.

(2) The LSTM based predictive model performs better in the mixed ground condition and the mudstone condition than in the round gravel condition. The proposed LSTM model is able to capture the variation patterns but may have the wrong estimations of peck values of AR.

(3) Compared with the RF model, the DFN model, and the SVR model, the proposed LSTM model performs best both in the R^2 values and RMSE values. The time hysteresis effect of the slurry and the soil, as well as the higher feature space of the LSTM model, may lead to the better performance of the proposed LSTM model.

Despite the above achievements, however, some further improvements should be made in this predictive model. On the one hand, the proposed model can only predict the AR at the next moment, which seems insufficient in assisting the real shield tunneling operation. What we proposed is to investigate the feasibility of the LSTM based predictive model. For better guidances in shield tunneling, it’s necessary to develop a multi-steps AR predictive model. On the other hand, the proposed AR predictive model can only tell the operators how the AR change as time grows, but can’t give suggestions on how to steering the tunneling parameters. Hence, if we want to realize the intelligent shield tunneling, it’s essential to build a cycle of prediction and control with intelligent methods, such as reinforcement learning, transfer learning.

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BIM and Computer Vision Integrated Approach for Indoor Positioning and Rescue Routing

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ABSTRACT: *It is of great importance to localize the trapped personnel both timely and accurately when emergency occurs. However, nowadays indoor positioning and path-finding methods are facing many challenges: (1) Most of the existing path-finding methods are based on two-dimensional floor plan, focusing only on the geometric information of interior space, and ignoring the topology information of architectural elements. (2) Unlike Global Navigation System(GNSS) solutions in outdoor environments, there are multiple challenges for indoor positioning, such as the immature spatial-temporal modeling approaches for indoor maps, the lack of low- cost and efficient method for positioning and path planning. In this paper, geometric and topology information has been extracted from IFC files for the process of generating the GNM (geometric network model). By using the computer vision method to recognize the static object, the primary location of the user is acquired. Finally, precise position is resolved by combining the world coordinates with the pixel coordinates obtained by SIFT (Scale- invariant feature transform) algorithm, which afterwards connects to the previous GNM, and the shortest rescue path is computed through Dijkstra algorithm. This paper takes a campus building as an example, and proves the feasibility of the proposed method.*

KEYWORDS: *BIM, Computer Vision, Path Planning, Dijkstra, IFC*

1. INTRODUCTION

Emergency response and pedestrian route planning rely highly on indoor geospatial data. For emergency response and pedestrian navigation, the integration of indoor information is important for rescue route planning. In the current practice, tactical and operational decisions for rescue missions are often determined onsite, planned through observations of blueprints and the physical space, and through improvisation in the disaster zone. Given the abundance of available data in BIM, the potential of making efficient and effective decisions should be reached in a better extent for both the survival and safety of rescuers and victims (Chen,2016). In addition to bridging of BIM to generation route planning, computer vision method can better understand the indoor environment and help to localize the rescuee. Thus, this paper focuses on developing an active indoor positioning approach which the rescuees can localize themselves by using the cell phone and automatically planning the route for the rescue team.

2. LITERATURE REVIEW

2.1 BIM-based Navigation Network Generation

Because of the separation of building spaces, each building spaces exists separately and is connected by corridors, stairs and other structures. Establishing a relatively independent relationship between building spaces, which is the generation of navigation network, is one of the keys to achieving indoor navigation. In recent years, with the development and application of BIM, the method of indoor path generation based on IFC standard has gradually attracted the attention of scholars. Teo et al. (2016) proposed a multi-purpose geometric network model (MGNM) based on BIM, and discussed the strategy of indoor and outdoor network connection. Establishing a parametric path planning sub-model based on IFC and building an indoor basic road network by Delaunay triangulation is one of the latest research directions. At present, some scholars have carried out relevant research (Lin & Lin, 2018). Isikdag et al. (2013) proposed a new BIM-oriented modeling method and defined a new BIM-based indoor navigation model (BO-IDM). Taneja et al. (2016) proposed three automatic generation algorithms for different types of navigation models, which can support map matching of indoor positioning data.

2.2 Vision based Indoor Localization

Recently, due to the popularity of smart phones, computer vision-based indoor positioning shows a broad prospect. Current vision positioning technology includes monocular vision positioning technology, binocular vision positioning technology and omnidirectional vision positioning technology. Klein & Murray (2009) implements SLAM algorithm online and in real time. It uses parallel tracking and mapping methods (PTAM) to simultaneously perform motion tracking and map building tasks. According to the difference of reference object selection, computer-vision based indoor positioning can be divided into reference building model, image, pre-deployment target, and projection target. For reference images, Kim & Jun (2008) compared views with image sequences of databases through AR (augmented reality). For reference building model, Liu et al. (2006) compared the feature points in the mobile phone image with the database (building plan). Werner et al. (2011) compared the as-built building model with the obtained photos, making full use of the prior information contained in the CAD model. But this method is only suitable for the space with more features such as edges and corners, and it is not suitable for the large open spaces. Based on pre-deployed targets, Mulloni et al. (2009) captured two-dimensional codes with a camera to obtain location information. Wu et al. (2018) developed a positioning system for smartphone cameras in large indoor spaces, which can achieve the precision of 1 meter in a range of 40 meters. Because of the complexity of the environment, there are still difficulties in indoor positioning. It is necessary to make comprehensive use of various positioning technologies. For example, Li et al. (2011) integrated WSN technology and RFID technology, combined with extended Kalman filter and particle filter method that effectively improved positioning accuracy.

3. METHODOLGY

The main idea of our system is to use smartphone images to locate users through static objects in the indoor environment and automatically generate rescue route from the BIM-based navigation network (as shown in Fig.1).

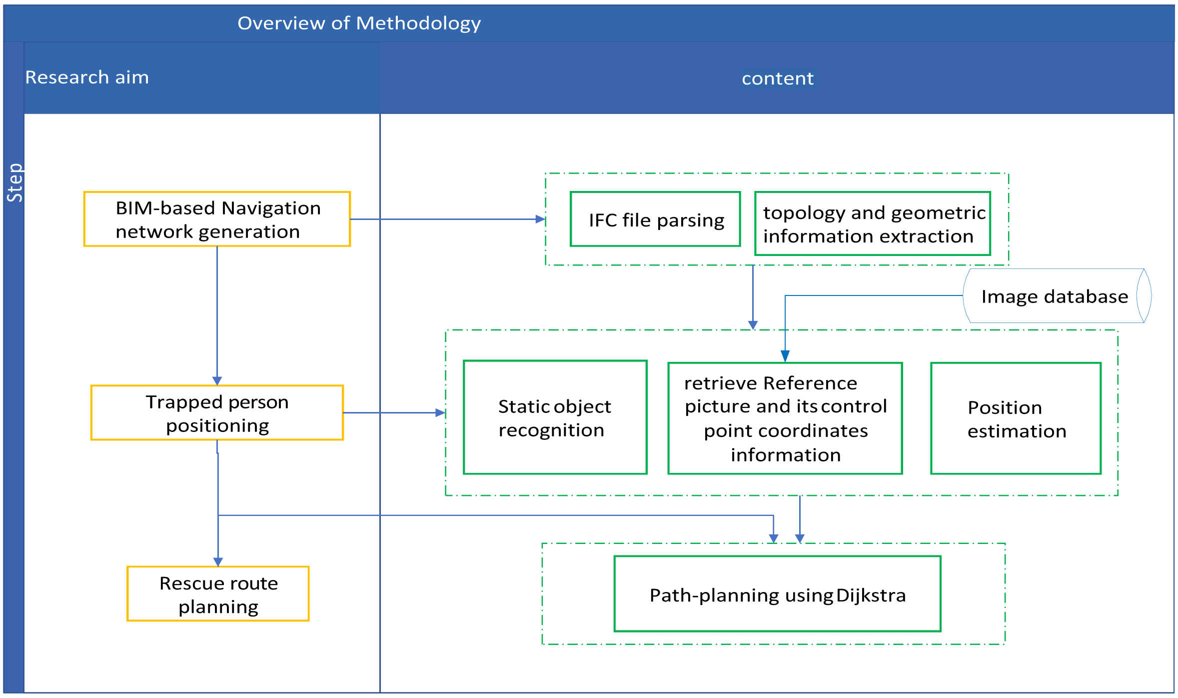

Fig. 1. overview of our proposed method

3.1 Geometric Network Model Generation Based on IFC

Since there are large number of indoor elements and their corresponding relationships defined in IFC files, this paper utilized geometric network model to define the relationship among indoor spaces elements. The geometric network model abstracts the navigation network into a graph which constitutes of nodes and edges, and records the correlation information between the nodes by using the adjacency matrix. For nodes $v1$, $v2$, $v3$, $v4$ … … vn, the relationship between nodes is expressed by the weighted adjacency matrix D. matrix $D[i, j]$ denotes the weight on edge $E(vi,$

vj).If edge $E(vi, vj)$between vi and vj does not exist, then $D[i, j]$ is infinity. The navigation network for interior space information mainly includes: space node, horizontal connection and vertical connection. (Table 1).

Table 1: IFC Indoor element types

Geometric network model elements		Space interpretation	Interior space element types	IFC entity types
node	space		room	IfcSpace
node		Horizontal entrance	door	IfcDoor
		Horizontal path	Corridor	IfcSpace
edge	Horizontal path		Room-door	IfcRelSpaceBoundary
edge	Horizontal path		Corridor-door	IfcRelSpaceBoundary
Vertical path			stairs	IfcStair

In IFC file, IfcProduct defines the common type information of all building products. To generate the spatial network, subclasses of IfcProduct, IfcProudctRepresentation and IfcObjectPlacement should be obtained. The former defines the geometric representation of building components, and the latter defines the coordinate attributes of components. Components in IFC adopt relative coordinate system instead of mapping coordinate system. Therefore, all components must be unified in the same coordinate system (IfcSite) by the transformation matrix obtained from IfcLocalPlacement and IfcAxis2Placement3D. In this paper, the node of each elements was simplified into its geometric center on x-y plane, and the Z value is lowered to the height of the storey.

$$\mathrm{N} = \left(\frac{X_{max} + X_{min}}{2}, \frac{Y_{max} + Y_{min}}{2}, Z_{storey}\right) \tag{3.1}$$

The positioning method in IFC components is a local positioning method which is realized by referring to the coordinate description of another coordinate system in one coordinate system and by multi-level chain reference. For example, the local coordinate system of floor refers to the floor coordinate system, while the local coordinate system of floor refers to the building coordinate system. (As shown in Fig. 2).

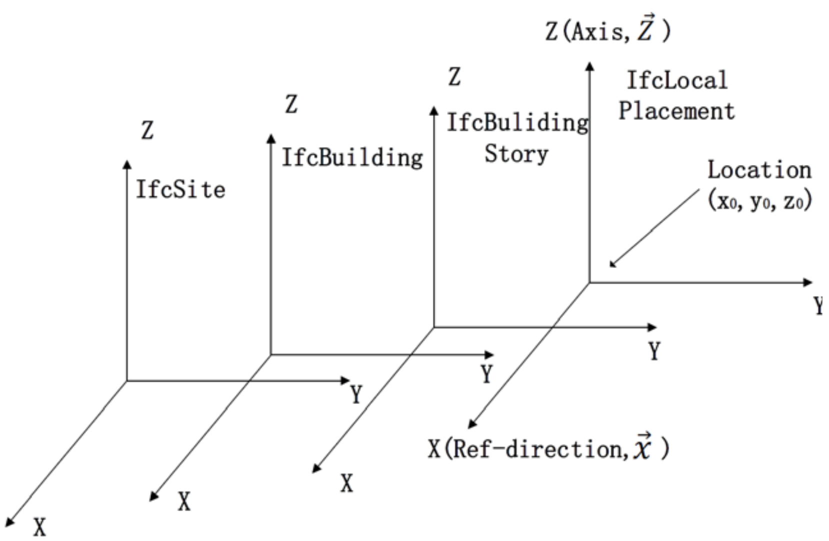

Fig.2. IFC coordinate system (Zhu et al., 2019)

Therefore, there is a relationship of rotation and translation between different coordinate systems. The coordinatesystems of mutual reference are connected by IfcAxis2Placement. The attribute 'Location' in IfcAxis2Placement refers to translation quantity, 'RefDirection' refers to the unit direction vector of X axis, 'Axis' refers the unit direction vector of Z axis, and the direction vector of Y axis can be obtained by calculating the outer product of the known unit direction vectors of X-axis and Z-axis. These vectors comprise the rotation matrix. The specific coordinate transformation formula is shown as follows (Zhu et al., 2019):

$$[x'\ y'\ z'] = [\mathrm{x\ y\ z}] \times ([\vec{x}\ \vec{y}\ \vec{z}]^{T^{-1}})^T + [x_0\ y_0\ z_0] \tag{3.2}$$

Here, x', y', z' are converted coordinates; x, y, z are the original coordinates; x0, y0, z0 are translations; x, y, z are the initial unit vectors of the X-axis, Y-axis and Z-axis, respectively.

3.2 Indoor positioning technology based on computer vision

This section introduced an real-time localization method for the trapped personal. The main steps include: 1) Collection images of static objects and setting three control points for each static object, of which their corresponding pixel coordinates and world coordinates were stored in the database.2) Recognizing the static objects and retrieve its corresponding reference picture and relating information; 3) Calculating the homographic matrix between real time image and the retrieved reference image, with which the pixel coordinates of three control points in the real time image can be obtained. Combined with the world coordinates, the position can be estimated.

According to the transformation relationship between the image coordinate system and the camera coordinate system, the relationship between the world coordinate system and the image coordinate system can be obtained (Xiao et al., 2018), the formulation is shown below:

$$\frac{X}{f} = \frac{u - u_0}{f s_x} = \frac{r_{11}x_w + r_{12}y_w + r_{13}z_w + t_x}{r_{31}x_w + r_{32}y_w + r_{33}z_w + t_z} \tag{3.3}$$

$$\frac{Y}{f} = \frac{v - v_0}{f s_x} = \frac{r_{21}x_w + r_{22}y_w + r_{23}z_w + t_y}{r_{31}x_w + r_{32}y_w + r_{33}z_w + t_z} \tag{3.4}$$

In the above formula,$_0$, v_0, $f\ _x$, $f\ _y$, s_x, s_y are the internal parameters of the camera, which can be obtained by camera calibration. r_{ij},t_x, t_y, t_z are the exterior parameter, which represent the rotation and translation quantity, respectively. As the translation matrix can approximately represent the users' coordinate (the translation quantity from world coordinate to camera coordinate), therefore this paper proposed that for each static objects in the indoor environment, three control points should be set so that the pixel coordinates and the world coordinates of each point can be identified and solve the equation of (3) and (4). This paper uses BIM coordinate system as the world coordinate system, which means the world coordinates of control points and location points is in accordance with the BIM coordinate system, so that the generated location points can be connected to the geometric network model directly.

3.2.1 Static Objection Detection & Identification

When the trapped person takes a photo, the primary task of the system is to detect static objects in the image and recognize their unique identities. This is a key module of the system, which can output the identification of static objects in the image. The feature extraction and matching of the static object boundary in the image which affects the performance of the image quality are carried out in the following procedures, and identifying the objectof the static feature is the key to find the corresponding attributes in the database.

Since Faster-RCNN network works well on object detection problem, this paper utilized transfer learning tactics to retrain a well performance network called Alexnet in order to achieve a satisfactory result with limited samples. The Faster-RCNN integrates region proposed, feature extraction, classification and rectangle refinement into an end-to-end network, greatly reducing the amount of computation and speeding up the detection process. The layer of the network is part of the Alexnet to achieve the feature extraction of smartphone images. Examples of the training dataset are shown in Fig. 3.

Fig.3. Examples of the training dataset

3.2.2 Obtaining Control Points Coordinates

Some feature points (such as the corner points of the door) in the BIM model of the static object are chosen to be control points. Since the pixel coordinates of the control points can be changed in different images because of different shooting angles. In two images containing same context, the *homographic matrix H*, can describe the transformation of the pixel coordinates of the same point.

$$\mathrm{H} = \mathrm{s}\begin{bmatrix} f_x & \gamma & u_0 \\ 0 & f_y & v_0 \\ 0 & 0 & 1 \end{bmatrix} [r_1\ r_2\ \mathrm{t}] = sM[r_1\ r_2\ \mathrm{t}] \tag{3.5}$$

$$X = H * X_{ref} \tag{3.6}$$

In the above formula, *M* refers to internal reference matrix, *s* refers to scale factor, r_1, r_2refers to the internal reference matrix of reference image and real-time image respectively, and *t* refers to the distance between two photographic positions. By using SIFT algorithm (LOWE, 2004), which can figure out multiple key points between two images, the homographic matrix can be obtained. Fig. 4 shows an example of output by the above algorithm. The pixel coordinates of control points in reference images are measured in the offline phase.

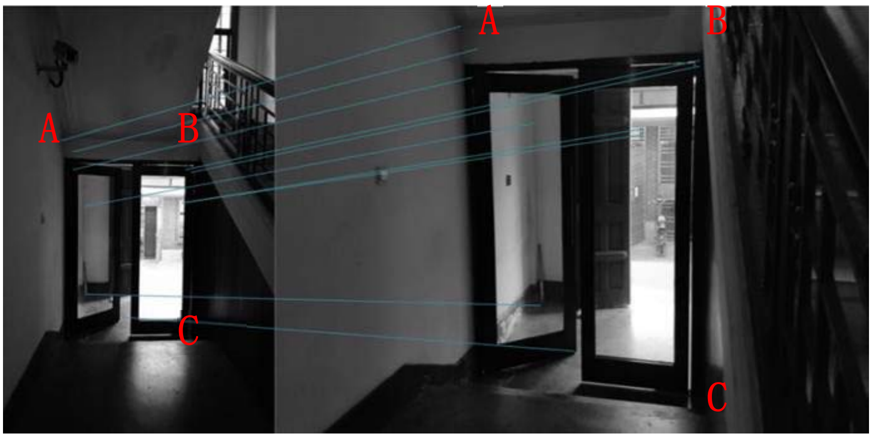

Fig.4. example of control points' matching

3.3 Rescue path generation

The Dijkstra algorithm is a widely used graph search algorithm in navigation and robotics. The cost function in this research is based on the actual distance of each node (Mirahadi & Brenda, 2019).

In Dijkstra, the start node is tagged first. Then, the cost of travel to all the connected nodes is calculated. The node with the smallest value is tagged. Then, the costs of travel to all of its connected nodes are calculated. The cost of unvisited nodes is updated if it is less than their previous cost. This process continues until the end node is met.

Large facilities and high-rise buildings typically have multiple exit doors. Therefore, there are multiple goals in this pathfinding problem. The Dijkstra algorithm is therefore solved for multiple exit goals and the minimum of those is the final solution.

4. CASE STUDY

The proposed method was tested in a two-storey campus building scenario. The prototype of IFC-to-GNM conversion for transferring information from BIM/IFC into GNM was implemented in two steps. Step 1 was implemented in the apstex toolkit to extract the corresponding IFC classes/relations. Step 2 was implemented in the Java environment and followed the relationships of the elements to calculate the topological primitives. The number of related elements is shown in Table 2.

Table 2: elements of GNM

GNM elements	Meaning	Element name	IFC classes	Numbers
Node	Space	Room	IfcSpace	38
	Space	Corridor	IfcSpace	1
	Horizontal protal	Door	IfcDoor	43
	Space	Corridor	IfcSpSpace	10
	Vertical protal	Stair area	IfcStairFlight	4
Edge	Horizontal route	Corridor	IfcSpace	8
	Horizontal route	Room-to-door	IfcRelSpaceBoundary	43
	Horizontal route	Door-to-corridor	IfcRelSpaceBoundary	42
	Vertical route	Stair	IfcStairFlight	2

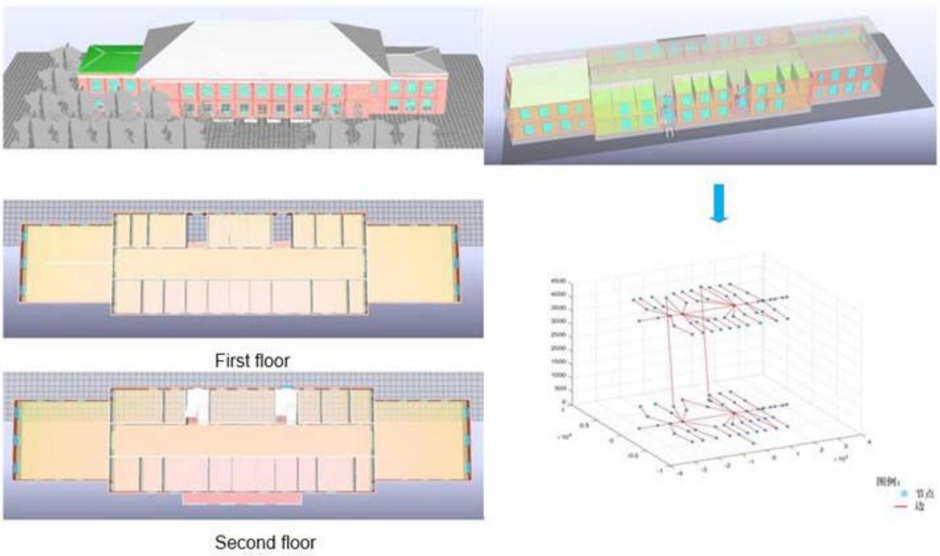

Fig.5. geometric network model generation

To verify the effectiveness of the indoor positioning method, Firstly, we choose the easy-to-catch static objects for the locating process. Image training set of static objects are taken from different angles, distances and under different illumination. Then, the Faster-RCNN network for detecting static objects was trained by using the transfer learning tactics. After the static object is recognized, its corresponding reference photos were retrieved for SIFT feature extraction process, the calculated homographic matrix is:

$$\begin{bmatrix} -54.96 & -17.24 & -0.02 \\ -17.05 & -39.79 & -0.02 \\ 26891 & 5500 & 1 \end{bmatrix} \tag{7}$$

Corresponding control point coordinates are shown in Table 3. The real-time image is captured by iPhone SE. The calculated camera's internal parameters matrix is:

$$\begin{bmatrix} 382.5 & 0 & 0 \\ 0 & 382.6 & 0 \\ 164.9 & 230 & 1 \end{bmatrix} \tag{8}$$

After obtaining the pixel coordinates and the world coordinates of the three control points and the camera internal parameters, the computed users' coordinate is (8247, 5200, 409) mm, with 1.69m positioning error from the practical measurement (9304,6071,1400) mm. Since the Z value is lower than 4000 mm, the trapped person is localized on the first floor. In order to facilitate path finding, the user's positioning coordinates are updated to (8247, 5200, 0).

Table 3: Pixel coordinate and world coordinate of the control point (unit: mm)

Pixel coordinate(reference)	Pixel coordinate(real time)	World coordinate
A_{ref}(544,141)	A(358,624)	(8123,8279,2000)
B_{ref}(1226,120)	B(1349,646)	(9723,8279,2000)
C_{ref}(1239,912)	C(1202,1104)	(9723,827,1)

Assuming that the trapped personnel is locate on (8247, 5200,0) and the rescuer start from (11890,3795,4000). Dijsktra algorithm was then run for each node based on the cost of distance. Table 4 shows the result of this calculation. The distance of each path is listed. The result shows that Route A should be selected as it is the shortest path for rescue.

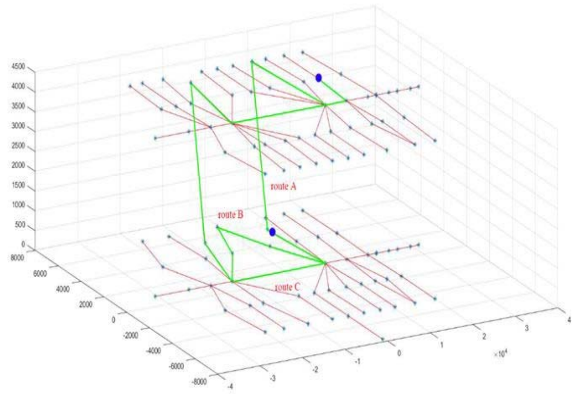

Fig.6. the alternative path for rescue

Table 4: alternative paths and their distance

Route	Distance(mm)
A:(11890,3795,4000)→(10142,1023,4000)→(5136,1023,4000)→(6036,6148,4000) →(8036,5523,0)→ (8247,5200,0)	18387.95
B:(11890,3795,4000)→(10142,1023,4000)→(5136,1023,4000)→(1358,1023,4000) →(-4864,1023,4000)→(-9864,1023,4000)→(-8974,5898,4000)→(-6974,5398,0) →(-4864,1023,0)→(-4864,3805,0)→(-464,6763,0)→(3936,3805,0)→(5136,1023,0) →(10142,1023,0)→(3936,3805,0)→(8247,5200,0)	70349.54
C:(11890,3795,4000)→(10142,1023,4000)→(5136,1023,4000)→(1358,1023,4000) →(-4864,1023,4000)→(-9864,1023,4000)→(-8974,5898,4000)→(-6974,5398,0) →(-4864,1023,0)→(1358,1023,0)→(5136,1023,0)→(10142,1023,0)→(3936,3805,0) →(8247,5200,0)	63934.04

5. CONCLUSION

This study proposed an indoor positioning and route planning method by integrating BIM and Computer Vision. This method used IFC to automatically generate a GNM of the building, and used Computer Vision method to localize trapped personal. A hypothetical case study showed that the proposed method can effectively provide a specific route for emergency response, highlighting the rich geometric and topologic information advantage of BIM and the Computer Vision based positioning estimation method.

Future work in this research requires a modification to the cost function in order to include other influential factors in Dijkstra path-planning like considering the safety state of each nodes. Further adjustment should be made in consideration of smoke diffusion, directional bias of the movements and congestion for a safer rescue route planning.

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Intelligent Construction Automation

Prediction of Building Energy Use Intensity and Detection of Outliers with Bagging Regression Models

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ABSTRACT: *As a major energy consumer, building occupies nearly one-third of the global energy consumption and greenhouse gas emissions. Controlling the building energy consumption (BEC) can effectively reduce the global energy consumption. To this end, it is crucial to give an accurate prediction of Building Energy Use Intensity (EUI). Various studies have been carried out using different prediction models. However, the widely used diagnostic methods and statistical regressions both have some limitations. The former usually is designed for specific cases and cannot be easily applied to other cases, while the latter cannot address the multicollinearity problem efficiently. Moreover, the majority of the previous studies only focused on a single experimental building or limited amount of buildings. There is a lack of studies that predict the building EUI at city scale to offer more comprehensive suggestions for urban planning. In addition, buildings with abnormally high or low EUI could uncover more valuable advice for energy-saving. Unfortunately, most of the existing literature studied the outliers simply based on the EUI value without considering the influential factors. Therefore, this paper proposes a methodology framework for EUI prediction and outlier detection at city scale combining the non-linear bagging method and regression models. Seven regression models are adopted and different types of buildings are studied. A case study is carried out in New York City to validate the effectiveness of the proposed framework. Results show that our methodology can improve the prediction accuracy of EUI and detect the outliers efficiently.*

KEYWORDS: *Building Energy Use Intensity; Machine Learning; New York City; Non-linear Bagging Models; Outlier Detection.*

1. INTRODUCTION

Energy is the lifeblood of modern societies. In the past decades, global energy consumption and associated carbon dioxide (CO2) emissions have increased significantly due to economic development and population growth. Major energy consumers include building, transportation, and industry. Among these, the building sector is considered as the largest contributor to the world energy consumption and greenhouse gas emissions. According to IEA Energy Technology Perspectives 2015 [2], the building sector occupies nearly one-third of the world final energy consumption and global CO2 emissions. It is estimated that by 2050, the global building energy consumption could increase by 50% over 2012 levels if no assertive energy efficiency action is taken [3]. Also, compared to the transportation and industry sectors, the building sector is reported to have the largest untapped energy efficiency potential [7]. This means energy efficiency programs aimed at the building sector can have significant impacts on reducing global energy consumption and greenhouse gas emissions.

Accurate prediction of building energy consumption (BEC) is crucial for establishing energy efficiency programs. It could facilitate the design and operation of buildings. Building Energy Use Intensity (EUI) is normally used to represent the energy consumption efficiency of a building. Many research has been conducted to predict the building EUI with different methods. Diagnostic modeling methods and data-driven methods are two typical approaches in existing literature. Diagnostic methods (also known as engineering methods or white-box models) model building EUI by simulating the laws of thermodynamics. They calculate building EUI based on detailed building and environmental parameters such as building construction details, operation schedules, HVAC design information, solar and shading information. For example, Shabunko et al. [32] used EnergyPlus to simulate the energy performances of buildings in Brunei Darussalam. Guo et al. [29] utilized eQuest to conduct an energy consumption analysis and simulated the re-design of the Civil Engineering Research Building at National Taiwan University. Yu et al. [24] applied TRNSYS to simulate the central air-conditioning system in classroom building. However, diagnostic methods usually are designed for specific physical buildings, systems and environment. When they are applied to other buildings and situations, a lot of parameters and model setting need to be re-adjusted.This is time-consuming and computationally expensive.

Data-driven methods, on the other hand, addressed some of the limitations of diagnostic methods. They can be generalized to different kinds of buildings and situations as long as enough historical data are given. Various kinds of data-driven models have been established to predict building EUI. Statistical regressions are one of the most popular data-driven models. For example, Fumo et al. [27] conducted a linear regression analysis for the prediction of building EUI for residential buildings. Bianco et al. [31] developed single and multiple regression models to forecast electricity consumption in Italy. Howard et al. [10] used a multivariate linear regression to estimate the annual energy end-use intensities in New York City. Lam et al. [18] developed multiple regression models to predict the energy use in air-conditioned office buildings in different climates. However, these regression methods have shortcomings. One major problem is that the prediction accuracy of linear regression models is relatively low as the real cases are complicated and the relationships between variables are non-linear. Therefore, it is necessary to design non-linear methodology frameworks that can improve the prediction performance.

Furthermore, most of the existing literature on building EUI prediction focused on a single experimental building or limited amount of buildings. For example, Fan et al. [11] predicted the next-day energy consumption and peak power demand for the tallest building in Hong Kong. Ekici and Aksoy [9] only selected three different building samples for the EUI prediction. Yang et al. [33] predicted the energy consumption for only one office building in Montreal. In fact, there is a lack of studies that predicted building EUI on the city scale or national scale. Predicting the EUI distribution in city scale and identifying the influential factors can offer more actionable suggestions on urban planning and policy making.

To fill these research gaps, this study focuses on the EUI prediction on city scale using non-linear machine learning algorithms. Energy consumptions of the buildings in New York City (NYC) are predicted. Also, we want to identify the buildings with extremely high EUI, because they should be paid more attention when improving the whole energy performance of the city. Buildings with extremely low EUI should be identified as well since possible energy saving policies could learn from their successful experience. Methodology to achieve the purpose is called outlier detection. It can help identify the abnormal energy consumption profiles. A number of studies have used outlier detection techniques in studying building EUI [17]–[19]. However, the majority of them detected outliers based on either merely the EUI value or the energy consumptions in several situations using clustering analysis. Their analysis did not take into account the influential factors and the interactions between these factors. A more objective outlier detection should be based on prediction models. Buildings that have much higher or lower EUI than the predicted value using high-performance models are more likely to be the real outliers.

To sum up, this paper proposes a research framework for Building EUI prediction and outlier detection at city scale. Bagging method is combined with regression models to non-linearly model the Building EUI in NYC. Seven different regression models are tested. Experiments are conducted to compare the prediction performances of non-bagging regression models and bagging regression models. Results show that the bagging method can significantly improve the prediction accuracy of the regression models. Performances of different bagging models for different building types are evaluated after that. Outlier detection is then conducted using the optimal bagging regression model and three sigma rule. Two typical outlier cases are analyzed in detail to uncover the reasons behind and propose practical suggestions. The rest of the paper is arranged as follows. Section 2 introduces the methodology framework. Section 3 presents the case study in New York City. Results and outlier analysis are shown in Section 4. Section 5 concludes the work.

2. METHODOLOGY FRAMEWORK

Figure 1 presents the methodology framework proposed in this paper. It consists of three parts, namely preprocessing, model optimization, and outlier detection. Firstly, building energy consumption data are collected and preprocessed. Methods such as missing value handling, data cleaning, feature transformation, and value normalization, are conducted to preprocess the data into a more model-friendly format. After that, the data are applied to the bagging regression models to predict building EUI. This is the second part of the framework. Seven different regression models are modeled and compared. The optimal one with the lowest prediction error will be selected as the best-fit model. The best-fit model will then be used to detect the outliers. This leads to the third part of the framework. In this part, outliers are detected using the best-fit model and three sigma rule.

2.1. Bootstrap and bagging

After data collection and preprocessing, the samples are formatted into a more suitable format for data mining. To improve the prediction accuracy for building EUI, non-linear bagging regression models are proposed in this paper. Just as the name implies, the proposed models combine the bagging method and regression models. Bagging is a commonly used ensemble learning method. It accomplishes the learning tasks by constructing and combining multiple learning models. It can help mitigate the overfitting and improve the modeling performance. Bagging method has been widely used and has achieved great performance in various problems, including classification, regression, and feature selection [8,15,25].

The training and validation process of the bagging method is shown in Figure 2. It first uses bootstrap to conduct random sampling with replacement for k times, and this gives k bootstrap sample sets and k out of bag (OOB) sample sets. Each set will train a weak learner and then validate it using the OOB set. Eventually, the model will average the validation results of all the k weak learners and get the OOB error. It can be seen that each case in the experiment data will have chances to be selected as either a training case or a validation case. Therefore, the training process in the bootstrap and bagging model has a relatively stable and objective result, and there is no need for cross-validation.

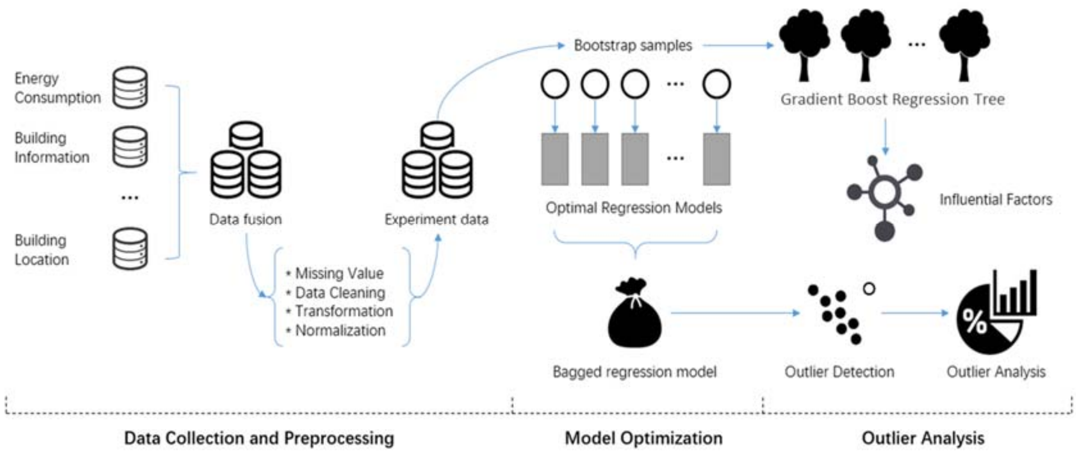

Fig. 1: Methodology Framework

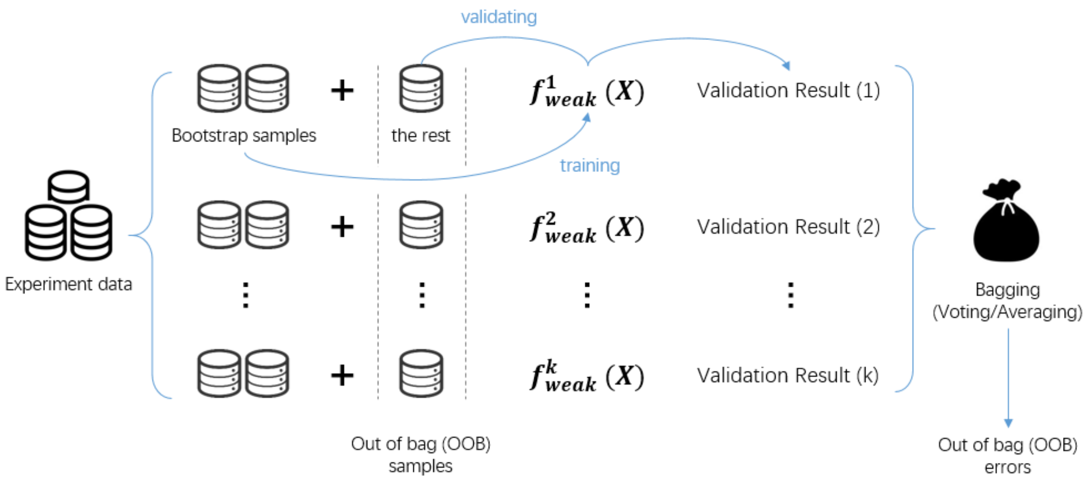

Fig. 2: The training and validation process in bootstrap and bagging

2.2. Prediction regression models

As mentioned above, for the k bootstrap sample sets given by bagging method, k weak learners are trained. Performance of the weak learner, obviously, will influence the final prediction results. Therefore, it is necessary to find the most appropriate learner. In our study, seven commonly used regression models are adopted as the candidates of the optimal base prediction models of bagging. They are Lasso Regression, Ridge Regression, K-Nearest Neighbors (KNN), Support Vector Regression (Linear SVR), Radial Basis Function SVR (RBF SVR), Multi-Layer Perceptron (MLP) and XGBoost. Since the algorithms mentioned above all have their own individual advantages, it is hard to decide the most appropriate one for this paper based on their theory. Performance of these algorithms for EUI prediction will be compared to find the optimal one through experiments in Section 4.1. The selected model will then be used to detect outliers.

2.3. Outlier detection using three sigma residuals

After the optimal model is given, it is used to help detect the building EUI outliers. Steps of detecting outliers are as follows. Firstly, calculate the predicted building EUI using the optimal model. Secondly, compute the difference between the predicted EUI values and the observed values. The difference is considered as the residual, which represents how much the real value deviates from the predicted value. If the predicted value is larger than the real value, the building is operating in a more energy efficient way than expected. If the predicted value is smaller than the real value, the building consumes more energy than expected due to some kinds of reasons. Therefore, this paper aims at identifying the buildings that have much higher/lower EUI than the model prediction. To accomplish the objective, three sigma rule is adopted. Three sigma rule is a simple yet widely used method for outlier detection. It considers an observation as an outlier if its least squares residual exceeds three times its standard deviation [30], [35]. Mathematically, set \mu as the mean value, σ as the standard deviation. If a value falls out from $[\mu - 3\sigma, \mu + 3\sigma]$ range, it is viewed as an outlier. Based on the range, outliers are detected and analyzed in this study.

Overall, this paper combines bagging and regression models to predict the building EUI and detect and analyze the outliers. The model can improve the prediction performance of non-bagging regression models and generate more reliable results for outlier detection. In the following of the paper, effectiveness of the proposed methodology framework is tested by a case study.

3. CASE STUDY

3.1. Data collection

New York City (NYC), United States, is selected as our studied area. The case study will implement the proposed framework to predict the city scale building EUI and detect abnormal buildings. Two datasets are collected from the Mayor's Office of Sustainability (MOS) and Department of City Planning (DCP) of NYC. They are 2017 Local Law 84 (LL84) dataset of NYC and Primary Land Use Tax Lot Output (PLUTO) dataset of NYC.

The first dataset contains information on building identification (postal code, street number, etc.), building energy consumption (such as site EUI) and building characteristics (year built, property type, etc.) in NYC in 2016. Buildings with more than 10,000 gross square feet in NYC are recorded. 11,697 rows of data are included. Each row represents a building or a collection of buildings in a single tax lot. The second dataset covers land use information and geographic data at the tax lot level in NYC in 2016. To benefit mathematical modeling, these two datasets are joined and merged based on the BBL index (Borough, Block and Lot). All the features in the first dataset are remained and eight features related to building EUI are extracted from the second dataset. After these, a dataset with 11,697 cases and 60 features is given. Table 1 summarized the 60 features.

Table 1 The collected features

Category	Example Features	Number
Building Identification	Property ID, Property Name, Postal Code, Street Number, Borough, etc.	16
Building Characteristic	Gross Floor Area, Primary Property Type, Year Built, Occupancy, etc.	23
Energy Consumption	Site EUI, Electricity Intensity, Natural Gas Use, GHG Emissions, etc.	21
Total		60

3.2. Data preprocessing

The collected raw data usually have some flaws, such as missing value, noisy data, and high correlational data [22]. Preprocessing is necessary before the data are applied to the model. This experiment preprocesses the data in three aspects, including missing value handling, data cleaning, and data transformation.

3.2.1. Missing value

First is the missing value. Among the collected 60 features, 20 of them have missing values. Firstly, features with high missing rate will negatively impact the model performance. Also, these 11 features are not significantly related to building EUI. Therefore, they are deleted. Secondly, it can be observed that features like Site EUI and Indirect GHG Emissions have a missing rate lower than 1%. Since the missing rate is relatively low, cases with missing values of these features are removed. After these, there still left two features: Weather Normalized Site Electricity and Water Intensity (All Water Sources). These two are potential important features of EUI. Therefore, they cannot be deleted directly. Also, since the former has a missing rate higher than 6% and the latter has a missing rate higher than 33%, directly deleting the cases with missing values would remove a large number of cases. Therefore, for the missing values of these two features, the median values of the same property type are used to fill the missing values. Also, a column of binary indicator for each feature is added. It is used to indicate whether the feature value is missing or not. In sum, 11,522 cases and 49 features are remained.

3.2.2. Data cleaning

Next, data cleaning is conducted to clean the noisy data. Noisy data includes noisy cases and noisy features. First is noisy cases. After an inspection of the collected 11,522 cases, we find that the Site EUI of some cases is higher than 10,000. This is obviously a wrong record of data. To ensure the effectiveness of the study, the three sigma rule is firstly applied here to exclude these noisy cases. Specifically, this study uses the cases with Site EUI lower than 10,000 to calculate the three sigma value. The calculated upper range is 650.32, so the samples with the recorded Site EUI higher than 650.32 are excluded. After this, there remained 11408 samples. The summary of the samples before and after sample cleaning are shown in Table 2.

High correlational data are handled after the noisy data are cleaned. High correlational data means the feature is highly related to the target or other features. For example, Source EUI (kBtu/ft²) has the similar meaning with our target Site EUI (kBtu/ft²). It will influence the accuracy of our model. Therefore, the feature Source EUI should be deleted. Also, features that have a high correlation with other features have the multicollinearity problem and contain redundant information. Such information will slow down the training speed and increase the model complexity. Therefore, some of them should be deleted. Pearson correlation coefficient is deployed to remove high correlational data. One of the two features in a pair that has a correlation coefficient higher than 0.8 would be excluded. The one that has a higher correlation with the target would be retained. After the data cleaning, 11312 samples and 24 features are remained. Site EUI is the label of the model.

Table 2 Attributes of Site EUI before and after the application of three sigma rule

	Count	Mean	Std	Min	25%	50%	75%	Max
Before	11522	281.12	8629.90	0.10	61.92	78.54	97.63	869265.01
After	11408	86.11	61.61	0.10	61.94	78.52	97.61	650.32

3.2.3. Log transformation and normalization

After data cleaning, we observe that the values of Site EUI (kBtu/ft2) follow an approximately log-normal distribution. As some machine learning models would be better at estimating the values following a normal distribution [28], values of Site EUI (kBtu/ft2) are log-transformed. The log-transformed distribution of Site EUI (kBtu/ft2) is depicted in Figure 3(a).

Furthermore, to benefit the further experiments, mitigate the influence of dimension and speed up the model training, normalization (also referred to as unit scaling or standardization) is applied to the numerical features [34].

4. RESULTS AND DISCUSSION

This paper aims at modeling building EUI and detecting abnormal samples. The bootstrap-bagging model and the regression algorithms are combined to accomplish the task. To test the effectiveness of the proposed methodology framework, three groups of experiments are conducted. The first group compares the prediction performance of bagging and non-bagging models. The second compares the performance of bagging regression models for different property types. The third group of experiments detects and analyzes the abnormal samples. All the experiments are run on a computer with 8 GB ram, Intel Core i5, Windows 7 operating system. The coding environment is Python 3.6. Mean absolute error (MAE) and mean square error (MSE) are used to evaluate the prediction performance of the models. Lower MAE and MSE scores mean better performance. The calculation of MAE and MSE are presented in Equation (1) and Equation (2).

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n} |y_{\mathrm{predict},i} - y_{\mathrm{data},i}| \tag{4.1}$$

$$\mathrm{MSE} = \frac{1}{n}\sum_{i=1}^{n} (y_{\mathrm{predict},i} - y_{\mathrm{data},i})^2 \tag{4.2}$$

where $y_{\mathrm{predict},i}$ is the predicted value at time t, $y_{\mathrm{data},i}$ denotes the observed value at time t, and n represents the number of test samples.

4.1. Comparison of bagging and non-Bagging models

The first experiment is the comparison of bagging regression models and non-bagging regression models. Seven regression models are adopted. They are Lasso Regression, Ridge Regression, Linear kernel Support Vector Regression (Linear SVR), Radial Basis Function kernel SVR (RBF SVR), Multi-Layer Perceptron (MLP) Regression, K-Nearest Neighbor (KNN) Regression, and XGBoost. The parameters of these regression models are set using the default values of the sklearn package in Python. The number of basic learners, k, is set as 100 for bagging models. Five-fold cross-validation is conducted for non-bagging models. MAE and MSE are used to evaluate their performances. Results are presented in Table 3.

Table 3 Comparison of bagging and non-bagging regression models

Method	MAE		MSE	
	Bagging	non-Bagging	Bagging	non-Bagging
Lasso	0.246	0.248	0.132	0.136
Ridge	0.201	0.232	0.108	0.131
Linear SVR	0.071	0.453	0.028	0.776
RBF SVR	0.186	0.190	0.085	0.088
MLP	0.483	0.603	0.617	1.004
KNN	0.212	0.220	0.099	0.104
XGBoost	0.163	0.179	0.065	0.083

It can be observed from Table 3 that all the seven regression models achieved lower MAE and MSE scores after they were facilitated with the bagging method. This proves that the bagging algorithm can improve the prediction performance of regression models. In addition, it can be seen from Table 3 that compared to other bagging models, Bagging-Linear SVR has the lowest MAE score of 0.071 and lowest MSE score of 0.028. Linear SVR also gets the most benefits from the bagging method. It has the highest MAE and MSE decrease after the implementation of bagging.

Furthermore, Robinson et al. [35] adopted several models, such as XGBoost, Random Forest (RF), Linear SVR, and KNN to predict the building energy consumption using the same dataset in this paper. Their results showed that XGBoost has the best prediction performance with the lowest MAE score. This paper also evaluates the performance of XGBoost, of which the results are presented in the last row of Table 3. It can be seen that in non-bagging models, XGBoost does perform the best with the lowest error indicators. This is in line with Robinson et al. However, after implementing the bagging method, its performance was surpassed by Bagging-Linear SVR. Note that the experimental target data and the preprocessing steps in this study are very similar with their study. This further proves that the bagging regression models, especially Bagging-Linear SVR, outperform other general regression models in predicting building EUI.

4.2. Goodness of fit

By using the best-perform algorithm, Bagging-Linear SVR, the predicted Site EUI values for all the property types are calculated. Comparison of the real EUI values and the predicted EUI values is presented in Figure 3(b). The horizontal axis represents the ground truth value, the left vertical axis represents the predicted value, and the right vertical axis represents the point density. Lighter color means denser points. It can be observed that most of the samples distribute along the red diagonal line. The R-squared measure of goodness of fit is 0.701. This value is also much better than the R-squared calculated by Robinson et al. in Section 4.4 in their article [35]. Their value on the same NYC dataset was 0.540.

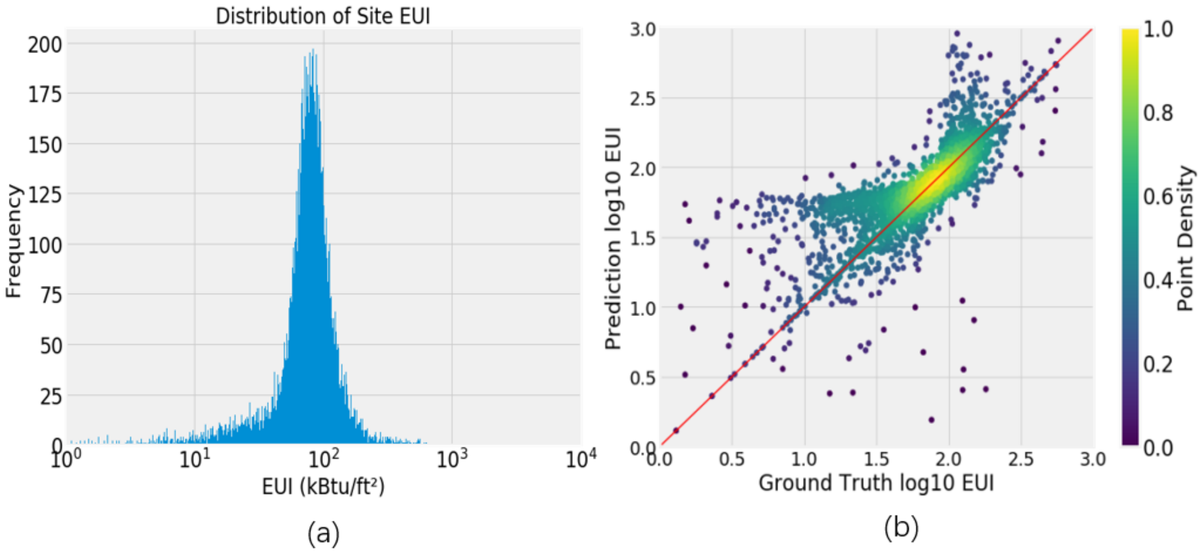

Figure 3: (a)Log-transformed normal distribution of site EUI (kBtu/ft2), (b)The goodness of fit of all the property types

Furthermore, it can be seen from Figure 3(b) that some of the data gather above the red line. These samples have higher predicted EUI values than the truth. These means the energy performance of these buildings is better than expected. They are defined as the positive points in this study. Also, some of the data distribute below the red line. This suggests the predicted values are lower than the real values. These buildings have higher building EUI than the expectation. They are the negative points. It is worth noting that the density of positive points is much denser than that of negative points. This means that, overall, NYC has much more positive buildings than negative buildings, which is not a bad sign for the government from the static angle.

4.3. Outlier analysis

4.3.1. Outlier detection

As Bagging-Linear SVR model exhibits the best prediction performance, it is used to help detect the outliers. Based on the methods introduced in Section 2.3, the residuals between the predicted values and the real values of the MFH samples are computed at first. The distribution of the errors is presented in Figure 4. It can be observed that the frequency of the errors approximately follows a normal distribution. Therefore, this study implements the three sigma rule to identify the outliers. Samples of which the values fall out from$[\mu - 3\sigma, \mu + 3\sigma]$ range are viewed as outliers. Result shows that there are 171 outliers. Among these outliers, 21 of them have higher real values than the predicted values. They are marked as negative outliers, because they consume more energy than expected. The rest 150 outliers have lower real values than the predicted values. They are marked as positive outliers.

Average EUI values of negative and positive outliers and normal samples are presented in Table 4. Different from traditional outlier detection methods that simply rely on EUI values, it can be seen that the average EUI value of negative outliers is not the highest. This is in line with our expectation that the true outliers are those hard to predict due to some unexpected abnormal features, but themselves do not have to have absolutely large or small values. The traditional value-based three sigma rule also follows this logic, but the thing is that it simply uses the mean value of the samples as the predictor. This study is proposing a model-based three sigma rule, and we use the best-performing model, Bagging-Linear SVR with 24 collected features, as the predictor. The detected outliers are expected to be more reasonable and reliable.

4.3.2. Case analysis

To further study the MFH outliers and the cause-effect behind, field investigations should be conducted. Due to limited data and information, this study only explored two cases as an example. These two are among the 171 outliers detected in the previous section. One is a positive outlier and the other negative. Basic information of the two buildings are presented in Table 5.

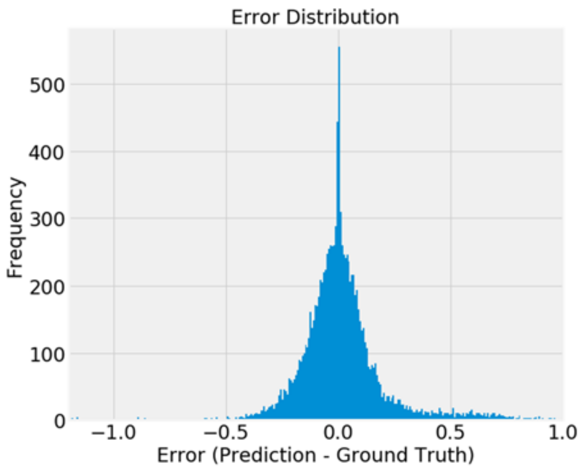

Figure 4: Error distribution of multifamily housing

Table 4 Average EUI values of negative outliers, positive outliers and normal samples

Cast type	Negative outliers	Positive outliers	Normal samples
Average EUI (kBtu/f2)	75.84	65.77	81.41

Table 5 Two typical abnormal samples

Property ID	Property Name	Borough	GFA	Year Built	Site EUI (kBtu/ft²)	Performance
4934469	Century-76 North 4th Street	Brooklyn	114160.0	2015	18.7	Positive
2643942	Harbor Hill HDFC	Brooklyn	50000.0	1995	123.2	Negative

The building with property ID 4934469 is named Lewis Steel Building. It is located in the heart of Williamsburg. Its former is 1930's steel factory. Now it is a residential building with 83 individually loft apartments. The building is Silver certified in LEED (Leadership in Energy and Environmental Design). Due to the advanced building design and equipment of new energy-efficient facilities, it requires less water and energy and generates less greenhouse gas during daily life. It can be learned from the case that during building renovation, the design and choice of energy-efficient facilities can have a crucial effect on building energy consumption. Following modern guidelines, such as LEED and Energy Star, may help improve the building energy performance a lot. Therefore, the NYC government could introduce more policies to encourage buildings to pursue related energy saving programs.

The negative case, with property ID 2643942, is located in Harbor Hill. It is a government-subsidized low-rent apartment that provides accommodation for low-income people. Most of the residents in the apartment are the elderly or the disabled. Due to the limited government funds and low income of the residents, the facilities of this apartment are cheap and old. The building was constructed more than 20 years ago and with no record of building retrofitting. The heating devices equipped could be less efficient, and tend to consume more energy. In addition, according to the census tract data of where the building locates, the people around this district has a relatively lower household income, and the district also has a lower percentage of people with bachelor degree or higher compared to the borough average. The lower household income can make the residents less likely to buy advanced energy saving but expensive household appliances. The lower educational level makes the residents have a possibly worse sense on energy saving. As a result, the actual energy consumption of the building can be much higher than the prediction from the general-fitting model. For such buildings, the governments should consider provide more funds on building retrofitting, give support to the low income families for advanced household appliances, and promote energy conservation activities to increase the awareness of the neighborhoods.

5. CONCLUSION

This paper proposes a non-linear methodology framework for building EUI prediction and outlier detection using the bagging method and regression models. Seven regression models are adopted in this paper, including Lasso Regression, Ridge Regression, Linear Support Vector Regression (Linear SVR), Radial Basis Function SVR (RBF-SVR), Multi-Layer Perceptron (MLP) Regression, K-Nearest Neighbors (KNN) Regression and XGBoost. Two datasets covering different kinds of buildings and characteristics are collected. Three kinds of experiments are conducted to validate the effectiveness of the proposed model. The contributions and discoveries of the study can be listed as follows:

- The bagging method can effectively improve the prediction performance of regression models.
- Compared to other algorithms, Bagging-Linear SVR has the best forecasting performance for building energy consumption.
- The outliers can be effectively detected using the proposed model-based three sigma residuals.
- Most of the EUI outliers in the case study are multifamily housings.
- Among the outliers, the number of positive outliers is far larger than the negative outliers. This suggests that NYC is at a positive status in managing building energy consumption from a static angle.
- Negative outliers may not have larger building EUI values than normal samples or positive outliers.
- To further reduce building energy consumption, the NYC government could encourage buildings to pursue related energy saving programs, such as LEED and Energy Star.

Due to the limitation in data availability, this study can be further improved in the following aspects. First is the range of features considered. If possible, it can be further extended to include occupancy features, facility details, and operation details. This can offer lots of possibilities to study energy conservation. Second is the range of buildings. The collected dataset only contains the EUI of buildings with more than 10,000 gross square feet. Buildings with smaller square feet could be further explored and studied. Last is the field investigation. This study only examined two cases due to the lack of information. More outliers should be further explored in practics for more energy conservation tips.

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Spatial-Temporal Ability Development Using Unmanned Aerial Vehicle (UAV) Visualizations from Construction Projects

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ABSTRACT: *Interpreting information related to Construction Engineering and Management (CEM) activities, such as in-situ planning and trade coordination, is a continuous challenge to the user. This information is pervasively used in projects by construction project personnel, and it can be viewed from two camps: spatial (how components, or physical resources, are related to one another) and temporal (the logic in a process, such as order, sequences, and hierarchies that transform physical resources). This paper presents a theoretical foundation to increase the users' ability to cognitively process spatial and temporal information, using aerial visualizations from Unmanned Aerial Vehicles (UAV). For this purpose, the researchers developed a novel and intelligent intervention for training (educational) that enabled a better understanding and awareness of CEM problems within construction practices. The UAV output is a mediation instrument that serves as an intervention for the interpreter. The interpreters experience a unique, 'bird's-eye view' of reality – a perspective that humans would otherwise not be able to observe directly. The technology effectively mediated and enhanced the physical world's perception through its ability to obtain aerial visualizations that integrate spatial and temporal information. A developed quantitative study in learning (training) settings looked at how the UAV output as the primary intervention impacted instructional and pedagogical tasks. Quantitative aspects included: (1) the effect of using UAV output (real-world aerial visualizations, text from cases) as a training method has on users' spatial-temporal skills and problem-solving; (2) the effect that the intervention has on users' knowledge acquisition and achievement of CEM, training-specific learning objectives.*

KEYWORDS: *Spatial-Temporal Ability; Unmanned Aerial Vehicles- Aerial Images; Learning;*

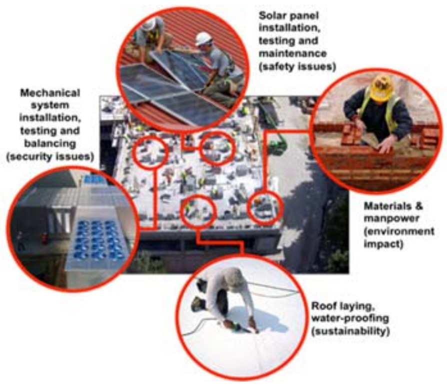
1. INTRODUCTION

Interpreting information related to Construction Engineering and Management (CEM) activities, such as in-situ planning and trade coordination, is a continuous challenge to the user. This information is pervasively used in projects by construction project personnel, and it can be viewed from two camps: spatial (how components, or physical resources, are related to one another) and temporal (the logic in a process, such as order, sequences, and hierarchies that transform physical resources). Understanding this information in a project site requires coordination and integration. It is imperative in many engineering contexts, as the processing of complex spatial and temporal information routinely impacts efficient reasoning and problem-solving in the management of construction-related activities.

Unmanned Aerial Vehicles (UAV) capture the physical construction-site environment through an ultra-high-definition camera and sensors (Engel, Sturm, & Cremers, 2014). The outputs are aerial visualizations (videos and images) coupled with telemetry data, such as geographical positioning, flight-path data based on the UAV's movement, and date and time information from the flight. This output offers a unique perspective. It enables the simultaneous visualizations of in-situ construction resources, processes, and management of activities as they unfold over time (see Figure 1). It supports the implementation of post-processing search and retrieval activities of UAV visualizations, sensing data for solutions to CEM tasks (e.g., follow-up the progress on specific locations within project controls). The output provides observers (users, construction project personnel) the opportunity to develop skills that integrate (Shelton & Hedley, 2004) procedural and configurational knowledge (Wickens & Hollands, 2000) by enhancing their understanding of interdependencies, interactions, and constraints among integrated and specialized engineering systems in the construction project.

The UAV output is a mediation instrument that serves as an intervention for the interpreter. The interpreters experience a unique, 'bird's-eye view' of reality – a perspective that humans would otherwise not be able to observe directly. The technology mediates and enhances the physical world's perception through its ability to obtain aerial visualizations that integrate spatial and temporal information. The UAV visually captures contexts in-situ, which constitutes a powerful resource for the interpretation of CEM practices. The mediation instrument affords experiential observations for awareness, which facilitates the development of supporting CEM activities, such as planning and goal prioritizing, that are essential for project site activities' success.

(a) Space-time conflicts: Management of resources in a small construction space.



(b) Safety hazards: In place inspection of temporary structures.

Fig 1: UAV images capturing resources (materials) and activities (trades) in-situ.

This paper reports on the impact and effects of using UAV output as the main intervention to understand the spatial and temporal information. The main sections of the paper are as follows. The first section explains the theoretical perspective of spatial-temporal ability. The second elaborates on the methodology used to test the subjects of the study. The third shows results and discussion and lastly the conclusions.

2. SPATIAL-TEMPORAL ABILITY: THEORETICAL FOUNDATIONS

In CEM practices, engineers are asked to process and integrate complex spatial information from various text- and image-based media. Their ability to effectively manage observations, however, is limited (Glick, Porter, & Smith, 2012), as is their ability to effectively process and internalize the functions and applications of (Tversky, 2005a) objects (e.g., construction products) and complex representations (e.g., engineering designs, drawings) of observed contexts of a project.

Based on the continued progress of events defined by time, temporal information frames conceptualizations such as simple motion (linear motion, rotation) and complex motion (assembling). The association of spatial and temporal information conceptualizes spatial transformations (aggregating two components into a single one), which requires knowledge on how to apply temporal information to the observed entities in the physical space. Thus, spatial and temporal information define construction processes using logical structures in the physical space.

We define the spatial-temporal ability as the CEM practitioners' abilities to process *spatial* and *temporal* information (P. Antonenko & I. Mutis, 2017; P. D. Antonenko & I. Mutis, 2017; Ivan Mutis, 2014, 2015; Ivan Mutis, 2017). This capability enables individuals to incorporate observations from the environment by drawing on *spatial* and *temporal* information from memory with higher-order cognitive tasks (e.g., reasoning) (Phillip L. Ackerman, 1992; Phillip L Ackerman & Cianciolo, 2000). The ability incorporates elements into memories within continuous cycles – from observation to simultaneous activities – of recalling and processing information. Spatial-temporal cognitive ability incorporates principles of spatial cognition and working memory (Center-, 2014) beyond the core understanding and processing of geometric shapes (Newcombe, Uttal, & Sauter, 2013; Wai, Lubinski, & Benbow, 2009) and movements. The effective integration of multiple sources of information and representations from observations with memory challenges spatial-temporal cognitive abilities (P. Antonenko & I. Mutis, 2017; Ivan Mutis, 2014; Torrance & Jeffery, 1999).

Spatial and temporal information is built within the CEM body of knowledge through the curriculum and associative episodes, such as recounts of sequences from the job site experiences. Associating spatial and temporal information compels mental simulations and reasoning (M. Hegarty, 2004). For example, the logical aggregation of materials of an assembly is based on the priority of assembly (Akinci, Fischer, Levitt, & Carlson, 2002). In the absence of direct observations, reasoning (higher-order cognition) for CEM occurs through mental simulation. When observations of CEM information occur, their integration with mental simulations facilitates higher-order reasoning by associating observations of in-situ information (construction materials and equipment) and representations (engineering designs).

2.1. Aerial-Visualizations and Spatial-Temporal Information

Traditional representations of designs (e.g., 2D drawings, BIM) inadequately address the complexities of applying, analyzing, and synthesizing designs to the physical context, which limits the practitioners' abilities to effectively manage their spatial visualizations (Glick et al., 2012) and to process and internalize (Tversky, 2005b) complex spatial and temporal information. Compared to the mental reconstruction of a set of separate static images or photographs (Wu, Klatzky, & Stetten, 2010) and relevant text passages, aerial visualizations are a much more effective medium. Figures 1(a) and 1(b) show an image, an instance of a continuous video stream input, from an actual construction project. This image represents an authentic physical context of construction, where multiple pieces of spatial and temporal information related to construction components and processes may be identified. The use of static images and virtual models does not enable users to experience the physical context's properties and is, therefore, sub-optimal for this learning outcome. On the other hand, BIM affords methods for understanding spatial configurations of designs in the construction process; however, they are limited because they are simulations and model only specific aspects of designs in 3D-rich virtual worlds. BIM's departure from the physical world's essential features and properties makes the users' experience fall short of the wide variety of real-world issues that they can encounter in-situ and therefore result in less authentic learning experiences with limited affordances of space and temporal information.

Aerial images assist and facilitate observers' awareness to solve CEM authentic problems (e.g., space management– which requires planning activities for potential conflicts). Aerial images are also be used to illustrate the use of materials, construction safety, and other critical issues in construction zones. They effectively integrate views of spatial visualizations (Glick et al., 2012) to process and internalize (Tversky, 2005b) spatial and temporal information. Aerial visualizations have the remarkable ability to enhance spatial information and optimizing cognitive processing of all visual information (Klatzky, Wu, & Stetten, 2008; Tang, Owen, Biocca, & Mou, 2003; Wang & Dunston, 2006) by eliminating the split attention effect through the integration of visual information into one dynamic view (Paas, Renkl, & Sweller, 2004; Sweller, Ayres, & Kalyuga, 2011; van Merrienboer & Sweller, 2010).

3. APPROACH AND METHODOLOGY

To investigate the role of aerial visualizations and spatial and temporal abilities in CEM practices, we developed a novel and intelligent intervention for training (educational) that enabled a better understanding and awareness of CEM problems within construction practices (see Figure 2). The technological innovation consisted of a prototype, conceptualized as an intelligent training environment, that enables users to retrieve typical construction projects' visualizations and cases. The technology environment mediates and enhances the perception of the physical world through its ability to obtain aerial visualizations that integrate spatial and temporal information (Shelton, 2003).

To approach the understanding of the perception of spatial-temporal information, we developed CEM cases to model the structure and dynamic of representative conceptual problems. Cases afford strategies and challenges employed by users as they solve authentic problems in-situ. Evaluations and assessments of our approach focused on the level of effort required in problem-solving within CEM cases. The use of technology and cases enabled the researchers to understand CEM scaffolding relative to cognition for problem-solving and metacognition for reflections and evaluations of actions and processes involved in problem-solving.

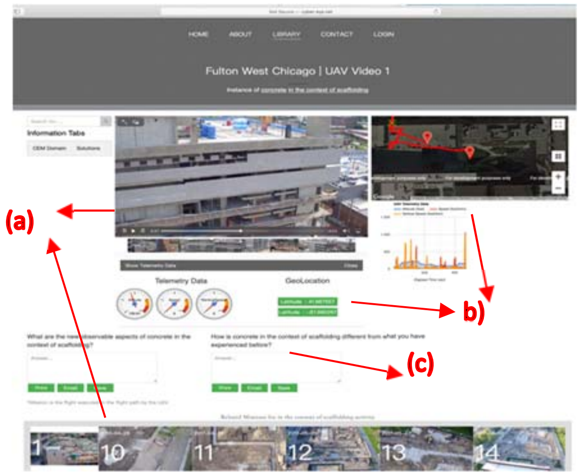


Fig 2. System output of the educational intervention: the retrieval of a CEM concept with the associated (a) aerial visualizations, (b) UAV data, and (c) questions that prompt reflection.

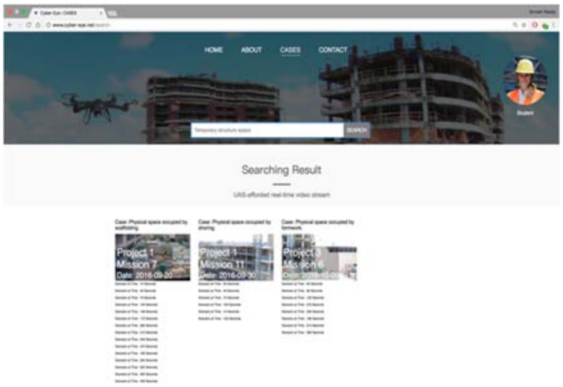
3.1. Cases Using Technological Innovation

Case building using technology innovation addressed the features of common CEM problems. Each case modeled the structure and dynamic of a significant CEM conceptual problem and alternative solutions through both a real job-site environment and aerial visualizations. Each case was framed using interactions between users (project personal, users) and incorporated input from experts. For this purpose, carefully constructed CEM problem-solution scenarios were created using visualizations and solutions from experts (researchers and instructors for CEM training). The scenarios modeled the experts' responses or reactions to CEM-problems. Information from the CEM problem-solution scenarios allowed CEM users to (1) interact with visualizations that represent the project's physical and social contexts and (2) register a dynamic that represents a process in-situ. The technical implementation of problem-solution scenarios was based on building information entities within specific sets of cases. These entities used CEM knowledge vocabulary. This approach registered the information of the experts' problem-solution experiences by classifying observed objects from UAV output, registering diagnostics, predictions, and sequences of actions (planning). Experts' input enabled the design of an algorithm that fires as reasoning. The experts' input was used to create and improve the library of cases.

Users were exposed to a complete set of variables and factors associated with a CEM problem by analyzing multiple cases (Gijselaers & Wilkerson, 1996; Hmelo-Silver, 2004). Analysis of several representative cases, each involving a unique aspect of the problem, allowed CEM users to create more flexible and adaptive mental representations and positively impact their ability to solve traditional and non-routine issues.

Experts and instructors populated the metadata of cases using semantic information and domain vocabulary, such as the widely used construction classification system, Omniclass (CSI, 2012). This input was associated with cases per observation of each UAV mission. Queries were based on the decomposition cases through keywords to retrieve associated cases based on matches of local similarities. The system may request additional keywords from the user during the inference process as programed in the reasoning module. The system output is the retrieval of associated UAV videos organized by UAV-missions and according to a hierarchy based on the relevance of similarity to the queried keyword (see Figure 3). The output allowed the user to select the most appropriate video image to work on solutions to problems in the cases.

(a) Key-word search function for UAV footage



(b) Categorization of UAV footage after search result

Fig 3: Educational intervention system functionalities.

3.2. Aerial image generation and UAV data from the job-site environment

Generation of aerial imagery is a benefit of using UAV as the technology platform for data acquisition. UAV uses a combination of technologies that are brought together to fulfill specific tasks. The system features three elements (Colomina & Molina, 2014; Everaerts, 2009): aircraft (UAV), ground control station, and a communication platform. Ultra-high-definition cameras and sensors (infrared [IR] positioning and proximity, IMU Inertial Measurement Units [IMU], accelerometers, GPS) within the UAV were used to capture specific aerial scenes on the job site. The UAV was strategically moved and positioned on-site to determine multiple geo-reference control points defined by the flight path (Engel et al., 2014), see Figure 4. Data were collected from local construction projects. The collected UAV-data was used to co-design cases using the UAV missions (Varela et al., 2014) that captured the main components of project contexts and CEM activities of interest.

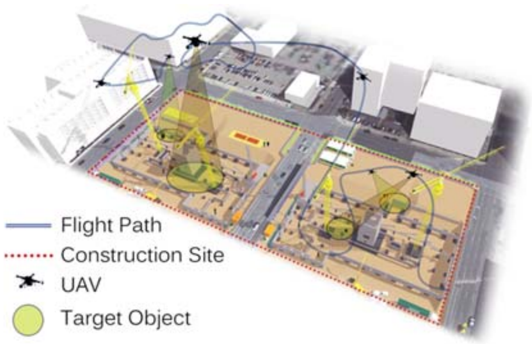


Fig 4. UAV Mission planning and management

The aerial visualizations and UAV telemetry data provided the users' affordances and tools to identify spatial-temporal information complexity, based on the input on CEM cases of interest. Without such visualizations, the users' awareness of project complexities would have proved difficult. UAV telemetry data included altitude, acceleration, and geo-reference information of the UAV flight-path (mission). Telemetry data is a new concept that provides the CEM user indicators that serve as references in the three-dimensional space. For example, the UAV location and altitude facilitate referencing building objects and equipment on-site to the airspace, enabling users to understand distances and time necessary to move materials by tower cranes.

Users had a high degree of control over the aerial visualizations and UAV telemetry data within case-related missions. For instance, by changing the UAV position in the flight path and the size of the visualization, users were able to observe changes in the level of detail of a target object and other physically associated contexts. Users could navigate through multiple missions from the whole set of UAV output (visualizations and telemetry data). For example, users queried CEM vocabulary relating to thermal issues due to the hydration of high-strength concrete on slabs. The retrieved output was cases and UAV output of high-strength concrete-cracking from buildings and infrastructure projects. The system was built using a client-server architecture implementation for information retrieval.

4. QUANTITATIVE INVESTIGATION

The quantitative study looked at how the UAV output as the primary intervention impacts instructional and pedagogical tasks. Quantitative aspects included: (1) the effect of using UAV output (real-world aerial visualizations, text from cases) as a training method has on users' spatial-temporal skills and problem-solving; (2) the effect that the intervention has on users' knowledge acquisition and achievement of CEM, training-specific learning objectives.

The quantitative study consisted of three steps: (1) pre-experiment, the treatment group was not exposed to *the intervention* (2) experiment, the treatment group was exposed to the *intervention,* and the control group used traditional learning materials, (3) data assessment, pre, and experimental comparison analysis. One authentic assessment (Richard J. Shavelson, 1994) was used for each experiment phase, herein Problem Solving Assessment (PSA). PSA was designed to measure users' skills for solving CEM problems. The focus, however, was on spatial-temporal ability. PSAs aim to assess both the process and products of the users' CEM problem-solving and solution justification abilities.

4.1. Pre-experiment

This phase aimed to assess the skills and knowledge focused on spatial-temporal abilities and motivations that users brought to the training session prior to the experiment. (e.g., abilities to recognize the presence of spatial and temporal constraints from designs, job site images). The instrument was a fully developed case (e.g., installing on-bearing capacity structures for effective management of space), which dealt with a specific CEM problem of interest (e.g., categorization of assembly elements to spatial and temporal interactions and availability). The cases were administered using materials for interpretation of designs (e.g., drawings and schedules).

4.2. Experiment

The tests were administered by reusing the pre-experimental phase cases for a new set of participants. The purpose was to observe possible causal relationships and changes in the tests between the pre-experiment and experiment phase and have the same source of information for comparison and analysis. The treatment group used the same CEM case, but it included UAV output (visualizations and telemetry data) as technology intervention (see Figure 5). The treatment group task observed a design component through a UAV output in our system output environment. The control group used and observed the same design component using traditional learning materials (e.g., drawings).

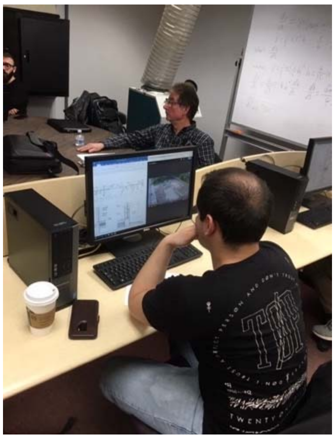


Fig 5. Experimentation using traditional and UAV outputs

4.3. Assessing Data

The comparative analysis enabled the researchers to measure the effectiveness of using the intervention. This design allowed comparisons between the two groups at different experimental phases producing implications for effective design and implementation of the innovation. These results helped the investigators to determine users' preconceptions and misconceptions, which were used to make corresponding learning arrangements in the next experimental phase and as a baseline to determine any improvements after experiments using the technology. For every design cycle, the researchers employed a mixed-methods research design and incorporated a range of relevant approaches.

4.4. Example of Experimentation

To illustrate the qualitative investigation, the following is a CEM working problem.

"*You are project engineering from a General Contractor (GC) organization. Your role is to plan and submit a bid for a commercial construction project. You, as professional project engineering of this GC firm, are required to estimate the price of some sections of the construction project. Due to limited time, you are required to execute a quantity take-off for the foundation wall and spread footing of one wall on one side of the building. You are to assume that the job site is flat ground before starting. The job site is near a batch plant.*"

The case is a foundation wall shown in Figure 6. Selected sections of 2D representations (drawings) of the foundation wall are shown in the Architectural and Structural drawings details in Figure 7(a). The 2D representations (drawings) are traditional materials used to interpret a design with CEM common practice. The intervention was the UAV output retrieved from a keyword search. The retrieved UAV output selection is the result of the construction of a problem-solution scenario (see Figure 7(b)). The current problem is a case that should be solved based on the solutions of similar past problems. The manual input on this selection represents a cognitive input towards the solution. Although the retrieved UAV output might not be a perfect match for the current case (i.e., the visualizations are not precise or optimal), their selection incorporates a rationale and a strategy from the observer to achieve the desired goal.

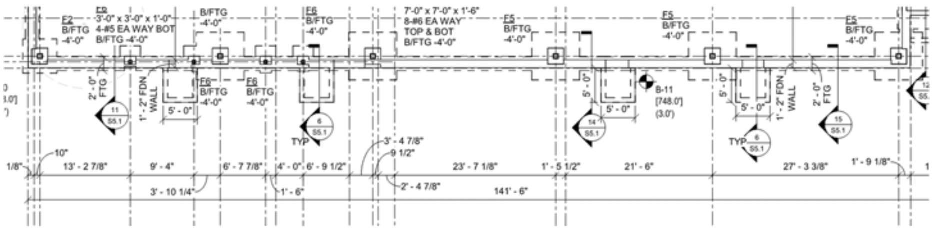
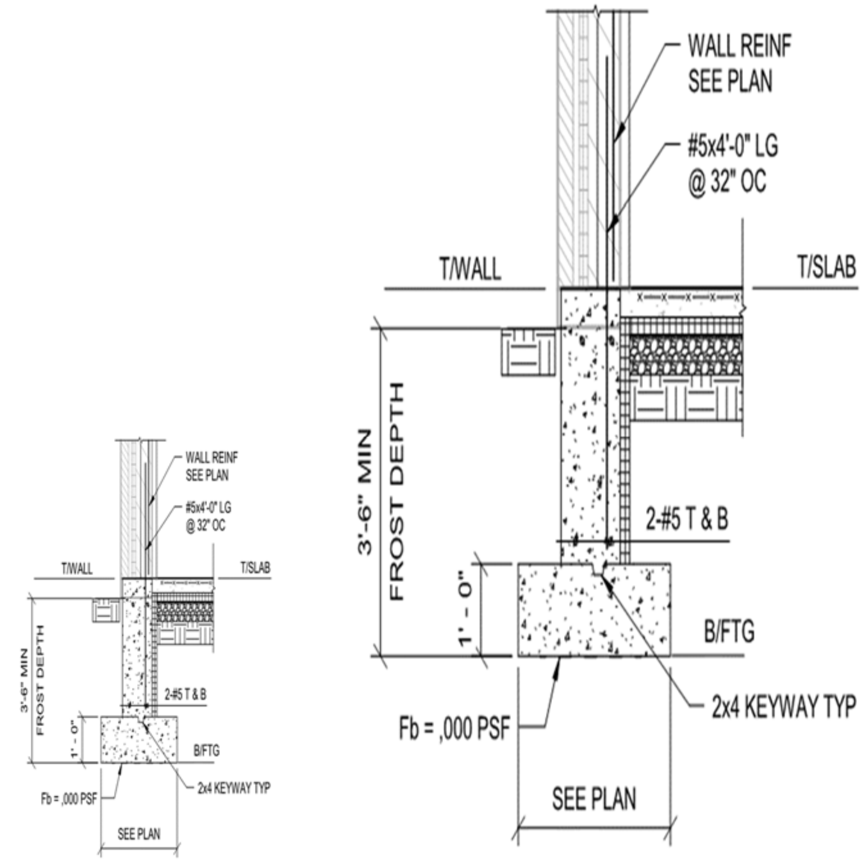
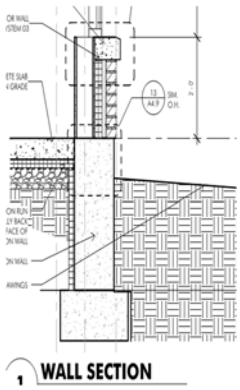
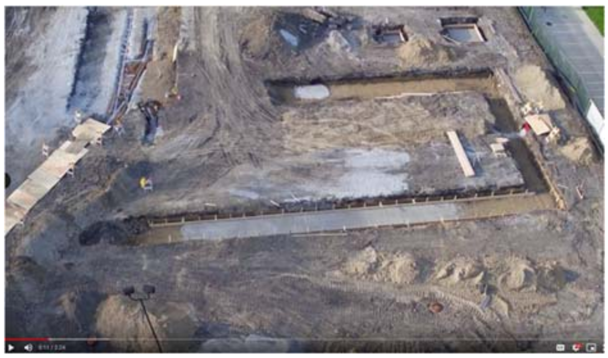


Fig 6: Excerpt of the 2D drawings of the wall section related to case.







(a) Architectural and Structural Sections of the wall

(b) UAV output of the system of a foundation

Fig 7: Traditional representation of design and UAV images for problem-solving (materials) and activities (trades) in-situ.

The following table represents the experts' approach to the number of items and the quantities to estimate the case.

Table 1: Take-off of the wall section

Line Items	Excavation	Forms	Keyway	#5 Rebar	Concrete	Backfill
Quantity	55 CY	496 SFCA	141 LF	600 LF	24 CY	34 CY

The experiments demonstrated that the UAV output incorporated affordances that informed activities of learning.

After the investigators' observations and interpretation of results, learners were able to observe, explore, reproduce, select, and state the defining problem features using visual and spatial information (e.g., they could break down the problem using aerial images as one resource for intervention). They were able to interpret data of a case to decide on spatial and temporal information and take actions when missing ambiguous information was presented.

5. CONCLUSIONS AND FUTURE WORK

Traditional medium for representation of designs (e.g., 2D drawings, virtual models (BIM), videos, images) inadequately address the complexities of applying, analyzing, and synthesizing designs (i.e., design interpretations) to the physical context, which limits the abilities of project engineers, project personnel, and CEM learners to manage their spatial visualizations effectively and to process complex spatial and temporal information. The use of static images and virtual models does not enable project engineers, project personnel, and CEM learners to develop experiences to connect spatial and temporal information to conceptualize spatial transformations in the physical context.

UAV output (visualizations and UAV fight related data), by contrast, do adequately presents context by (1) capturing images from construction job site environments and integrating real-world spatial-temporal features, and (2) enabling the contextual analysis of construction processes. UAV output provides unique technological affordances for democratizing access by dynamically creating and remixing learning materials to enhance the processing of real-world contexts. It provides affordances for learning and knowledge-building scaffolds and opportunities to interactively tailor visualizations to the learners' specific needs in a dynamic that provides meaning to spatially and temporally distributed information.

The design of the new project should enable CEM practitioners to incorporate concepts and practices into cases relevant to a particular CEM problem of study using a more accurate system for search and retrieval. Therefore, the design should include an intelligent approach for the search function to find compatible cases among past solutions that are more or less compatible with the new aspect of the target case. Future work will investigate learning processes using a new intervention technology environment to address the critical need to develop effective spatial-temporal abilities.

6. ACKNOWLEDGEMENT

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Automated Layout Design for General Hospitals Based on Healthcare Systematic Layout Planning (HSLP) Method and Genetic Algorithm (GA)

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ABSTRACT: *In recent years, with the increasing demands of health care and the accelerated development of medical equipment, the design and construction of hospital buildings has become increasingly demanding and complicated. However, the traditional layout design method for hospital buildings is labor intensive, time consuming and prone to errors. With the development of BIM technology, the automated design method has become possible and is considered to be more suitable for the layout design of hospital buildings. This paper proposes an automated design process based on Healthcare Systematic Layout Planning (HSLP) method and Genetic Algorithm (GA), which aims to solve the optimization problem of the space layout of large and comprehensive hospitals.*

Such process concerns the following three steps: i) based on the conventional Systematic Layout Planning (SLP) theory, developing the Healthcare Systematic Layout Planning (HSLP) method, identifying the relationship and flows amongst various departments/units, and arriving at the preliminary plane layout design; ii) establishing mathematical model to optimize the building layout by using the Genetic Algorithm (GA) to obtain the optimized scheme; iii) using a real hospital building layout design as case study to prove the effectiveness of this automated design method.

KEYWORDS: *Healthcare Systematic Layout Planning, Genetic Algorithm, automated design, layout design of hospital*

1. INTRODUCTION

Hospitals are designed to provide healthcare and life-saving services with complex and comprehensive functional layout [1]. With the continuous improvement of people's living standards, the investment in the healthcare facilities has gradually increased. This, together with the fast advancement of medical equipment and technology, has rendered more sophisticated requirements for the design of hospital buildings. In the hospital layout design, apart from the general rules of the conventional buildings, the following key issues should be specially taken into consideration as the main guiding factors, namely, i) the effective use of space to reduce the crowd, ii) the rational organization of the flows (e.g., clinic process flows, the logistics of goods, patients) facilitating the designated functions; iii) meeting the standard requirements of the codes in practice for healthcare facilities. These additional rules certainly enhance the level of complexity of hospital design. To obtain an optimized layout design scheme in the conceptual design stage has always been a great challenge and usually demands labor intensive iterations. At present, such design often relies on the designers' experience and thus is somewhat a subjective decision rather than an optimized one. In addition, Chinese hospitals are different from other public buildings, which have less unique artistic style but more modular and replicable features. This is exactly similar to the logic of mathematical model algorithm. Therefore, it naturally raises the necessity of developing an automated, and yet, rational design procedure. By introducing the Systematic Layout Planning (SLP) method into the design of hospital buildings, this paper intends to establish a quantitative model for the layout planning. Such planning schemes will be optimized by using Genetic Algorithm (GA) where the shortest path of patients is set as the optimization target.

1.1. Characteristics of Hospital Buildings

Contemporary healthcare buildings, e.g. hospitals, are medical spaces with various medical facilities and personnel, where people obtain treatments for their physical and mental health illness. Because of their complicated functions, hospital buildings possess many special characteristics. For instance, they should contain many special rooms housing unique medical equipment and devices such as X-ray, CT and DSA, which often have specific requirements for radiation and vibration protection. The types and layout of hospital service facilities such as cables, ducts and pipes are much more complicated. In addition to HVAC systems that are common in conventional buildings, there are many more special systems used for oxygen provision, purification, disinfection, radiation protection and medical wastes deposing systems [2]. The designers should consider these systems to be rationally organized, fulfilling their functions and, if needed, to be independently maintained during their service life. Another important characteristic of the hospital design is the function-oriented feature, namely, the key center of the design is to provide a streamlined space facilitating the effective and efficient treatment of patients. The concept of so–called "patient-centered" is now the main principle of hospital building design [3].

The above-mentioned characteristics creates imparts high level of complexity in procedures for designing of hospital. Surrounding the medical treatment flow, the space can be organized by two perspectives. One is from the transportation flow routes containing the patients, hospital personnel, goods, and service facilities. While the other aspect is from the space requirements for the public, clean, sterile, and contaminant zones. These two superimposed systems occupy the entire hospital space which creates many overlaps and should be defined by many parametric variables. The following governing rules should be addressed in developing the design scheme: streamline the diagnosis and treatment procedures; the maximum space utilization; the shortest people and goods flow routes; the compliance with the space controlling rules. The traditional design method has become inherently difficult to reach an optimal solution while meeting all these rules, so the design automation technology is sought to overcome such difficulty. A quantitative model for the layout planning is established on the basis of Systematic Layout Planning (SLP) method. This method considers the route of products as the core factor while the design of hospital considers the route of patients as the core and the remaining have various constraining/dependence relationship with patients. Therefore, it is reasonable and feasible to apply the improved SLP method to the specific healthcare facilities.

2. HEALTHCARE SYSTEMATIC LAYOUT PLANNING（HSLP）

2.1. Systematic Layout Planning

Facility Layout Planning (FLP) refers to the most appropriate space design for personnel, equipment and materials in the given site, in accordance with the whole process of receiving raw materials, manufacturing products and transportation of finished products [4]. The most effective combination of layout planning for maximum economic benefits has been widely used in logistics and industrial engineering. Among all layout planning methods, the Systematic Layout Planning (SLP) proposed by Joseph [4] is the most well-known and widely used one. This method is not only suitable for factory and production site design, but also for the layout design of service facilities such as hospitals, schools and office buildings. Based on the facility layout and flowchart analysis, SLP method establishes the relationship of amongst the functional units, and proposes a grading representation for each relationship. In doing so, this method transforms the original qualitative layout design into a quantitative model.

Specifically, the SLP method takes the product (P), quantity (Q), routes (R), service (S) and time (T) as the given basic elements for the layout planning procedure [5]. A good application of SLP can achieve the minimum material cost and route distances with the maximum efficiency and system optimization. The four stages of the entire SLP are divided as follows:

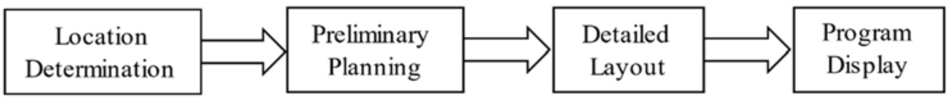


Fig. 1: Stages of SLP

2.2. Procedure of HSLP

The above mentioned SLP is extended to the hospital layout design (referred as HSLP hereafter). The overall procedure is as follows:

(1) Preparation of initial data

Collect the initial data P, Q, R, S, T specially for hospital buildings, which are patients, patient number, treatment routes received by patients, service departments and time. Carry out an overall analysis on these data.

(2) Analysis of the human flow relationship

An important part of the layout design is the analysis of the human flow. For hospital buildings, the walking route of patients is the core of the entire process as indicated by the fact that reducing the movement distance can improve the work efficiency. Flow intensity analysis and flow correlation diagrams are often used to represent flow relationship. The flow intensity is divided into five levels in SLP, which are represented by capital letters A, E, I, O and U with a decreasing strength score 4-0 [6].

Table 1: Flow Relationship classification

Letters	Score	human flow intensity	non-human flow relationship
A	4	super high	absolutely necessary
E	3	very high	especially important
I	2	high	important
O	1	middle	ordinary
U	0	low	unimportant

(3) Analysis of the non-human flow relationship

For the hospital building layout planning, apart from the human flow analysis, the relationship between the various functional units, i.e. the non-human flow relationship, is equally important. The factors considered by the non-human flow relationship are more comprehensive. The intensity of the non-human flow relationship can also be divided into five levels, i.e. A, E, I, O and U.

(4) Production of the relationship table

Considering of the actual scenario of applications, the relationship weights of the human and non-human flows in the design is considered realistically, and a relationship table is prepared for the further analysis.

(5) Drawing the location diagram

The correlation diagram of the hospital building layout is drawn based on the basis of the relationship table. The location diagrams of each functional unit in the actual layout can be obtained according to the relationship level.

(6) Preliminary layout plan

Incorporating the constraints of the actual conditions such as the specifically designated space sizes, reasonable adjustments can be made to obtain the preliminary layout plan. At this stage, a multiple feasible scheme can be proposed.

As the procedure suggests, the HSLP method is a systematic layout method with strict design principles and rigorous analysis, having strong practicality and operability. The above steps can be presented in a flow chart as follows:

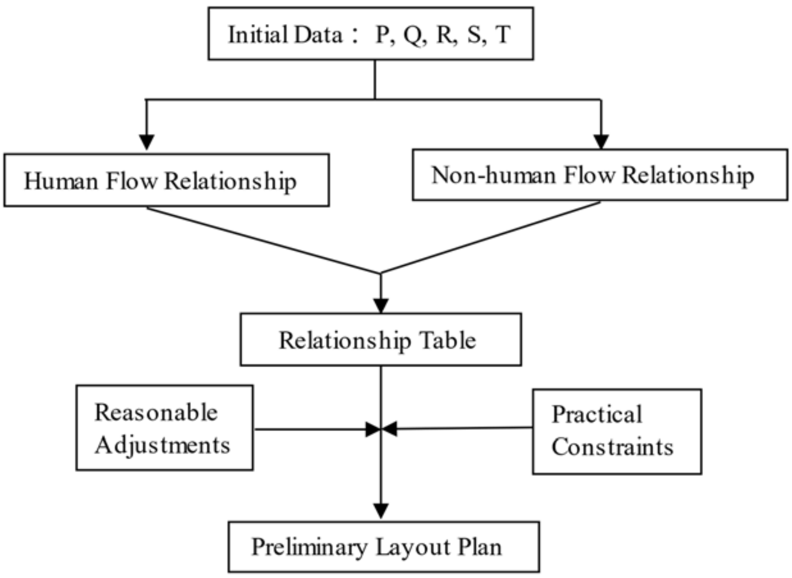


Fig. 2: Procedure of HSLP

Although the HSLP method has strong practicality with quantitative design procedures and rigorous analysis technique, it is still affected by subjective factors and may lead to different results by different designers. Tedious manual adjustments will be made to meet the real constraints. As the Genetic Algorithm (GA) has been proven an effective method on optimization, therefore, this paper employs it to improve the HSLP method by automatically adjustment of design instead of using the traditional manual adjustment method.

3. OPTIMIZATION OF LAYOUT DESIGN BY GENETIC ALGORITHM

3.1. Mathematic Model

The real layout problem is very complicated involving many variables. To order to introduce the mathematic model, the following assumptions are adopted:

(1) The functional units of the layout are rectangular and both side lengths are known.

(2) The functional unit areas do not overlap each other and are arranged in parallel to the edges of site.

(3) The walking path of the patient is calculated on a straight line.

The GA is very effective at finding optimal solutions to a variety of problems. This innovative technique performs especially well when solving complicated layout problem in building design [7]. There are usually three basic elements in GA optimization problems: variables, constraints, and objective functions. According to the above assumptions, the main factor involved in the hospital building layout planning is the number and streamlining of patients. Therefore, the variable is the order of the functional units in the layout; the constraints are the real constrains of each unit as introduced in the assumption; the objective function is the distance function of the patient treatment process. The optimal layout design of the hospital building refers to the solution of the two sets of basic solving variables, i.e., the human flow sizes and the distances between each two functional units.

According to the related knowledge of engineering management, the mathematic can be established as follows

$$Z = \min\left\{\sum_{i=1}^{n}\sum_{j=1}^{n} F_{ij}(k)D_{ij}(k)\right\} \tag{3.1}$$

Where: $F_{ij}(k)$ represents the number of patients from the ith unit to the jth unit in the kth layout planning, which is a human flow matrix. $D_{ij}(k)$ represents the distance between the center point of the ith unit to the jth unit in the kth layout planning, which is a distance matrix. Z represents the sum of the walking distances of the patients in the kth layout planning.

The choice of fitness function directly reflects the effectiveness of GA. In order to facilitate the good progeny individuals to be quickly inherited into the population of next generation, the reciprocal of objective function value is usually used as the fitness function [8]. This fitness function is mathematically written as in equation 2:

$$F(x) = \frac{1}{1+Z} \tag{3.2}$$

3.2. Procedure of GA

GA optimization of hospital building layout design can be performed using the following steps:

(1) Enter the initial data, P, Q, R, S, T. Following the second part of this paper, the human flow and non-human flow analysis are carried out to obtain the distance matrix and human flow matrix between the functional units.

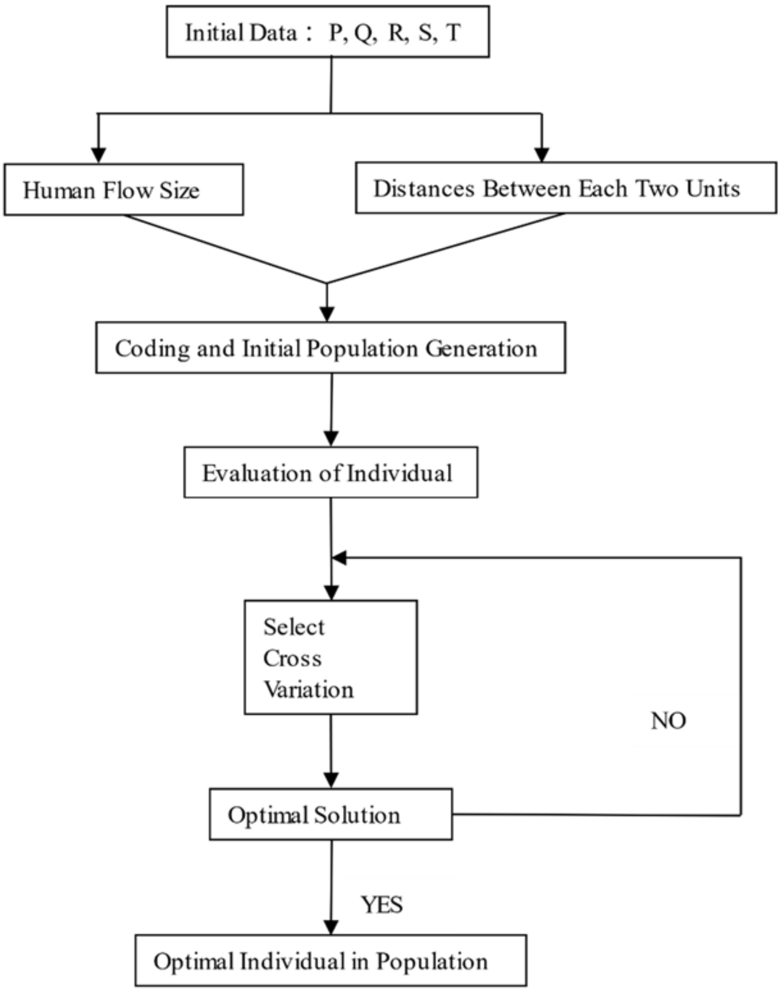
(2) Individual coding and population initialization. Each individual element in the GA is a layout order of the hospital building, which can be used as a coding rule to encode chromosomes and form an initial population.

(3) Detection and evaluation of individual fitness in the population. According to the objective function, the appropriate fitness function can be written. And the weight of everyone is judged by the value of fitness.

(4) According to the principle of survival of the fittest to identify genetic operators, crossover operators, mutation

operators and perform a series of genetic operations to obtain child chromosomes.

(5) Perform Step (4) on the generated child population until the iteration ending requirement is met.



The flow chart of the above steps is shown below:

Fig. 3: Procedure of GA

4. CASE STUDY

4.1. Application of HSLP

To demonstrate the application of the proposed method, a case study is performed in this section. For the simplicity purpose, this case only considers the surgery department of a general hospital. Firstly, 10 functional units are assumed to be included in the designed space, which are numbered as 1-10. The daily average flow statistics between units are shown in Table 2. Following the steps of the HSLP method, determine the human flow and non-flow relationship between each unit according to the survey of the existing surgical department and the expert knowledge based. The main influencing factors are the number of doctors, nurses and patients flow, the working connections between medical personnel, the closeness of the connection between medical personnel and the ward, etc. Finally, combining the human flow and non-human flow relationship to determine the ratio of the relative importance between these two as 2:1, which is summarized into a relationship table, as shown in Table 3. According to the HSLP method, the proximity value of a functional unit reflects whether the unit should be at the center position or at the edge position in the layout planning [4]. According to the data in the table and the actual conditions, a variety of alternative layout diagrams can be obtained, one of which is shown in the Figure 4. The more connections between the two units in the diagram, the closer the relationship is.

Table 2: Daily Average Flow Data (Number/day)

	Rest 1	Dressing 2	Preparation 3	Recovery 4	Nurse station 5	Instrument 6	Bath 7	Surgery 8	Storage 9	Cleaning 10
Rest1	0	45	0	0	15	4	10	28	2	0
Dressing 2	45	0	9	0	18	0	7	32	0	0
Preparation 3	0	9	0	13	18	0	14	32	5	3
Recovery 4	0	0	13	0	26	3	19	35	6	1
Nurse station 5	15	18	18	26	0	35	38	40	31	26
Instrument 6	4	0	0	3	35	0	4	12	12	0
Bathroom 7	10	7	14	19	38	4	0	22	8	21
Surgery 8	28	32	32	35	40	12	22	0	25	37
Storage 9	2	0	5	6	31	12	8	25	0	0
Cleaning 10	0	0	3	1	26	0	21	37	0	0

Table 3: Functional Unit Relationship

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
R1	/	A	U	U	E	U	O	I	U	U
R2	I	/	U	U	I	U	U	E	U	U
R3	U	U	/	E	E	O	O	E	O	U
R4	U	U	E	/	E	O	O	A	O	U
R5	E	I	E	E	/	E	E	E	I	I
R6	U	U	O	O	E	/	U	E	I	U
R7	O	U	O	O	E	U	/	E	O	U
R8	I	E	E	A	E	E	E	/	I	E
R9	U	U	O	O	I	I	O	I	/	U
R10	U	U	U	U	I	U	U	E	I	/
Proximity value	8	9	12	13	24	10	10	26	11	5
Sort	9	8	4	3	2	7	6	1	6	10

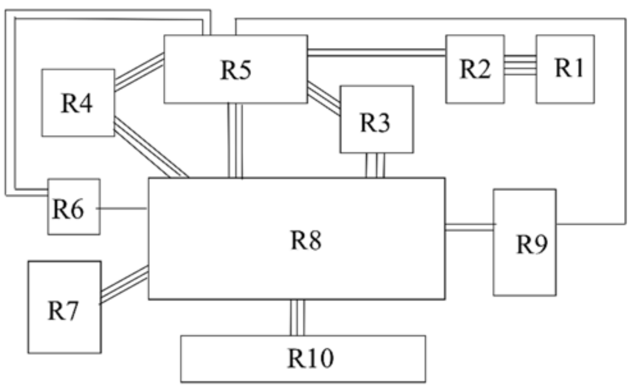


Fig. 4 Preliminary Layout Planning

4.2. Application of GA

The above results are taken as part of the initial population of the GA, and other initial layouts are randomly generated. Following the optimization steps of GA, the automated layout design is realized by MATLAB coding, and the overall site shape can be fixed in the initial implementation process to increase the calculation rate.

Set the population number P = 100, the crossover probability Pc = 0.9, the mutation probability Pm = 0.05, the maximum iteration number G = 400. And repeat the calculation 10 times with the above parameters. The target function Z after each run can be obtained, that is, the minimum walking distance value of the patients in this layout, as shown in Table 4. It can be seen from the table that the change of the objective function value during 10 times is not large. The reason is that after using GA optimization, the genes of the child population are basically the same, which leads to the smoother change of the fitness function value. The least value of objective function i.e. 5736m is obtained after third iteration. Finally, incorporating the additional requirements from designers, the realistic optimal layout can be obtained. The ideal layout is shown in Figure 5.

Table 4: Functional Unit Relationship

Trial	Objective Value(m)	layout
1	6536	10 8 9 2 4 1 5 6 7 3
2	6592	9 10 4 7 2 1 5 6 3 8
3	5736	10 9 8 6 7 4 5 3 2 1
4	6440	10 7 8 2 1 4 6 3 5 9
5	7056	2 1 7 3 4 9 5 8 6 10
6	6908	9 4 10 3 2 6 1 5 7 8
7	7256	2 3 7 9 4 1 5 8 6 10
8	6652	10 4 9 1 2 8 5 3 7 6
9	6488	8 9 2 1 3 4 7 6 5 10
10	6800	10 2 8 7 3 1 4 5 6 9

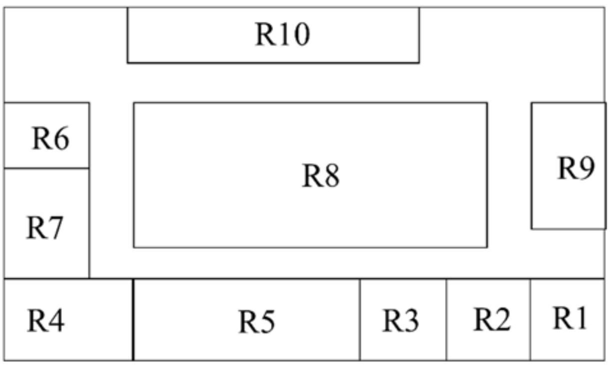


Fig. 5 Ideal Layout Planning

5. CONCLUSION

This paper adopted improved HSLP method and GA to establish layout optimization model of hospitals, and obtained the layout optimization scheme by solving the model. The layout problem of healthcare buildings was regarded as a mathematical optimization problem and the application of GA in the layout model greatly improved the quantifiable accuracy. The uncertainties of layout affected by subjective factors was reduced to a certain extent. Through the demonstration of the real example, it is observed that the proposed method provides an efficient and simple layout design of hospitals. Although the coding is simple, the solution shows that GA improved objective value indeed. It is particularly, in case of buildings over large scale with many complex functional units, this type of automated design method can give clear superiority. However, this paper failed to consider the special shape of the functional areas and the assumption about the layout is too simplified, which has a certain gap with the practical situation. Future work may apply the methodology described in this paper to real-world case studies instead of hypothetical spaces. Also, make a specific and reasonable design on the internal medical streamline.

6. ACKNOWLEDGEMENT

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Risk and Safety Management in Construction

Ontology-Based Risk Assessment and Solution during Shield Tunnel Construction

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ABSTRACT: *The complexity and risk of tunnel construction always affect people, economy, and environment. But the management, sharing and reusing of risk knowledge of tunnel construction have always been inconvenient due to the weakness of traditional information management methods such as the relational database. However, currently, ontology has become an important method of knowledge representation, management, sharing and reusing, which enables efficient and semantic information retrieval and highly facilitates knowledge sharing and reusing, and it can be the solution for the above problems. At present, few studies focus on the use of ontology of tunnel construction, and the ontologies built by them still have some shortcomings. For example, the solutions for risk must be given by reasoning (e.g. SWRL), and the construction order and hierarchy cannot be expressed. In this paper, an ontology of shield tunnel construction is developed and then applied based on WBS and risk analysis of the shield tunnel construction, which eliminates the shortcomings mentioned above. Firstly, this paper makes WBS of shield tunnel construction. Secondly, the risk analysis of shield tunnel construction is developed after proposing the relationships between risk factors, risk precursor, and risk accidents and collecting relevant data of the above three risks. Then, the ontology of shield tunnel construction is developed by Protégé. Finally, the ontology is applied. This paper takes an actual shield tunnel subway construction project as an example, creates its related instances and uses SPARQL to query the risks and corresponding solutions in it. The results show that the risks and corresponding solutions can be correctly identified, which can provide a guidance for construction safety.*

KEYWORDS: *ontology; shield tunnel construction; risk management; risk precursor*

1. INTRODUCTION

The complexity and risk of tunnel construction always affect people, economy, and environment. Due to the differences and uniqueness of tunnel construction, the transfer, sharing and reusing of tunnel construction risk management knowledge have always been inconvenient. The weakness of the traditional risk management method lies in the management of information, i.e., the storage and retrieval of information. Traditional information management methods mostly store knowledge as text or in relational databases, and information retrieval methods are mainly based on keyword matching, which can only identify literally matched information, but not understand information at the semantic level. In addition, the knowledge stored by traditional methods faces enormous difficulties when they need to be reused, such as different or improper information expression, insufficient mining and utilization of information (Zhou *et al.*, 2019), and data fragmentation of different systems (Lin *et al.*, 2019). However, ontology can be the solution for the above problems.

In the field of artificial intelligence, (Neches *et al.*, 1991) first gave the definition of ontology, "An ontology defines the basic terms and relations comprising the vocabulary of a topic area as well as the rules for combining terms and relations to define extensions to the vocabulary". The most used definition of ontology was from (Gruber, 1993), "Ontology is the specification of a conceptualization". Nowadays, ontology has evolved into an efficient and significant method for knowledge representation, management, sharing, and reusing.

At present, few studies focus on the use of ontology for risk management of tunnel construction. (Jiao, 2015) built a risk ontology for subway construction. (Zhong and Li, 2015) proposed an ontological and semantic approach for the construction risk inferring and application. However, the solutions for risks given by the above two researches relied on reasoning (e.g. Semantic Web Rule Language, SWRL), which should be used only if ontology cannot express and may cause redundancy in ontology after running multiple times. And these researches cannot express the order and hierarchy in the construction. (Hu and Huang, 2014) introduced a tunnel data organization method driven by ontology, which used some terminologies such as tunnel object, process, event, etc. like Industry Foundation Classes (IFC) to build a tunnel ontology. Nevertheless, this method cannot express risk well since it is similar to IFC, and need to combine expert knowledge to analysis problems manually. In this paper, an ontology of shield tunnel construction is developed and applied based on WBS and risk analysis of the shield tunnel construction. The shortcomings mentioned above are eliminated, so the solution can be represented in ontology instead of SWRL and the construction order and hierarchy can be expressed. It is worth noting that the method proposed by this paper is not final, but can be a foundation and provide ideas for future works.

This paper is structured as follows. Section 0 makes WBS of shield tunnel construction. Section 0 conducts risk assessment and solution with precursor analysis of shield tunnel construction. In section 4, the ontology of shield tunnel construction is developed. In section 5, the ontology is applied in an actual project. Finally, section 6 summarizes this paper and points out some future works.

2. WBS OF SHIELD TUNNEL CONSTRUCTION

A work breakdown structure (WBS) in project management and systems engineering, is a deliverable-oriented breakdown of a project into smaller components. According to some Chinese standards (GB50446-2017, STB/DQ-010001-2007) and related researches (Jiao, 2015; Liu, 2013), this paper firstly divides the shield tunnel construction into the following five categories: *Construction Preparation, Shaft Excavation, Shield Enter/Exit, Shield Excavation, Engineering Acceptance*.

Then, the WBS second level of the shield tunnel construction can be obtained by a consecutive decompose for each category above, as shown in Fig. .

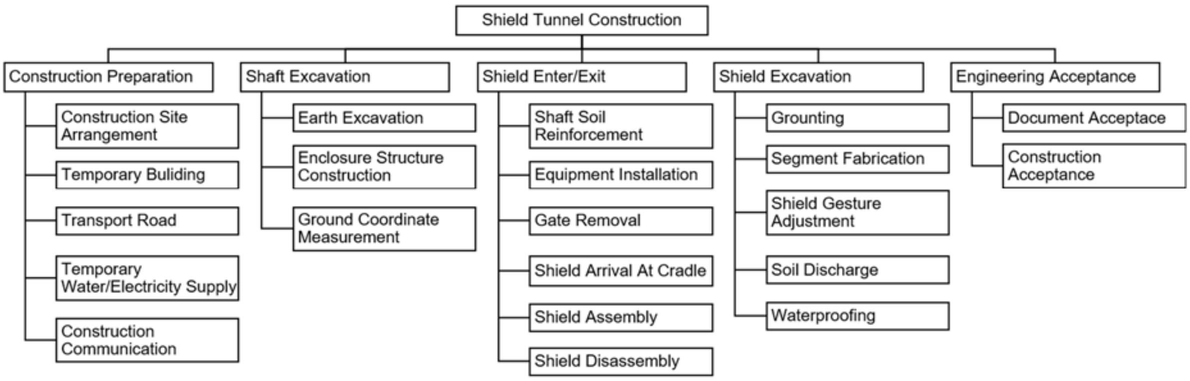


Fig. 1: WBS (1^{st} and 2^{nd} level) of the shield tunnel construction.

3. RISK ASSESSMENT AND SOLUTION WITH PRECURSOR ANALYSIS

Some researches about the application of risk precursor in the field of engineering have been made. (Weick and Sutcliffe, 2002) considered that the establishment of accident precursor information system can encourage effective and continuous communication between teams, and thus enhance their safety awareness. (Grabowski *et al.*, 2007) also believed that the identification of precursors before accidents' happening has great potential for improving the safety of the system.

However, the definition of some terms related to risk is still not clear and not unified. A now commonly used risk generation mechanism of tunnel engineering is, "Due to the existence of risk-pregnant environment and induction of risk factors, it may cause risk events and further damage to various risk-affected elements" (Cheng, 2004). Based on the above definitions and related researches, this paper proposes the concept of three risk elements, namely, *risk factor*, *risk accident*, and *risk precursor*. Their definitions are as follows, their relationships are shown in Fig. 1, and their details will be discussed in section 0-3.3.

- Risk factor. The direct cause or factor that can cause a risk accident.
- Risk accident. The event that deviates from the expected target or brings losses to the project.
- Risk precursor. A monitorable event that is generated by risk factors, which can predict risk accidents and has a higher frequency and less harm than the risk accident.

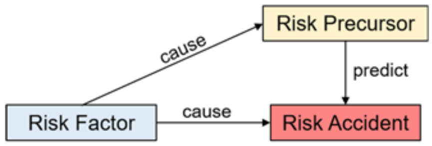


Fig. 2: the relationships between risk factor, risk accident, and risk precursor.

3.1. Risk factors and solutions

At present, researches on risk factors divide factors into some aspects: human, management, machinery, material, and environment. This paper combines some risk factors above, and will discuss them in three aspects, namely, human, mechanical, and environmental risk factors.

As for human risk factors, the "Swiss Chess Model" proposed by (Reason, 1990) described four levels of them, each of which affected the next level. Based on it, (Shappell and Wiegmann, 2000) proposed the Human Factors Analysis and Classification System (HFACS), which further subdivided the contents of its four levels and gave examples of possible instances in each level. Based on HFACS, (Wang *et al.*, 2010) established a construction accident analysis model HFACS-CI, which proposed a fifth level (external factors) above the fourth level of HFACS. By synthesizing the above researches, Table gives the human risk factors in shield tunnel construction.

As for mechanical risk factors, Construction Accident Cause (ConCA) model (Gibb *et al.*, 2006) divided the causes of equipment and materials into three categories: suitability, usability, and condition. This paper considers the combination of equipment and materials risk factors as mechanical risk factors, thus,

Table 2 gives the mechanical risk factors in shield tunnel construction.Finally, the environmental risk factors are divided into three categories, as shown in Table 3. This paper takes some instances in Table 1~Table 3 as examples and gives their solutions, as shown in Table 4.

Table 1: human risk factors in shield tunnel construction.

Level	Risk factors
Unsafe acts	Errors
	Violations
Preconditions for unsafe acts	Adverse mental states
	Adverse physiological states
	Physical/mental limitation
	Crew resource management
Unsafe supervision	Inadequate supervision
	Planned inappropriate operations
	Failed to correct problem
	Supervisory violations
Organizational influences	Resource/acquisition management
	Organizational climate
	Organizational process
External factors	Economy/social/political environment

Table 2: mechanical risk factors in shield tunnel construction.

Category	**Risk factors**
Equipment	Equipment performance
	Equipment suitability
	Equipment condition
Material	Material performance
	Material suitability
	Material condition

Table 3: environmental risk factors in shield tunnel construction.

Category	Risk factors
Natural environment	Whether condition
	Geological condition
	Hydrological condition
	Natural disaster
	Environmental damage
Surrounding environment	Surrounding underground pipeline
	Surrounding buildings
	Surrounding load
	Surrounding dangerous facilities
Working environment	Site arrangement
	Physical environment
	Sanitation

Table 4: solutions of some risk factor instances in shield tunnel construction.

Risk factor instances	Solutions
Shield tail sealing failure	Brush grease on seal frequently
(Mechanical)	Assemble segments centred
	Grouting the leaking part
Slurry low quality	Replace the slurry
(Mechanical)	Use a better performance slurry
Layer difference	Detecting information ahead
(Environmental)	Adjusting excavation parameters
	Adjusting shield gesture
Excavation obstacle	Ultrasonic obstacle detection
(Environmental)	Use stone crusher

3.2. Risk precursors and corresponding risk accidents

(Jiao, 2015) listed the monitorable information in subway construction according to the WBS of shield tunnel construction, which is similar to the risk precursors in this paper. Based on Jiao's research and related standards, Table gives the risk precursors in shield tunnel construction, and Table gives these risk precursors' limitation and corresponding risk accidents.

It is worth noting that the monitorable risk precursors listed in Table does not mean that they can only be monitored within their belonging constructions. For example, "ground settlement" in shaft excavation also can be monitored in shield excavation.

Table 5: risk precursors (monitorable) in shield tunnel construction.

Construction	Construction decomposition	Risk precursors (monitorable)
Construction preparation	Construction site arrangement	Site completeness
	Temporary building	Office security
	Transport road	Transport safety
	Temporary water/electricity supply	Water consumption
		Water supply pressure
		Power supply voltage
	Construction communication	Communication quality
Shaft excavation	Earth excavation	Shaft depth and size
		Distance from the nearest building
		Surrounding buildings deformation
		Surrounding pipeline settlement
	Enclosure structure construction	Enclosure wall maximum displacement
		Enclosure wall top displacement
		Ground settlement
		Soil deep settlement
	Ground coordinate measurement	Measurement accuracy
Shield enter/exit	Shaft soil reinforcement	Reinforcement area width and length
		Reinforcement soil compressive strength
	Equipment installation	Component installation deviation
		Component strength and stability
	Gate removal	Soil collapse amount

		Water leakage amount
	Shield arrival at cradle	Cradle deviation
		Segment vertical deviation
Shield excavation	Shield gesture adjustment	Shield axis deviance
		Jack position and thrust
		Excavation speed
	Segment fabrication	Segment quality
		Segment position deviation
		Segment joint opening
		Misalignment of adjacent segments
		Tunnel settlement
		Internal deformation
		Tunnel longitudinal deformation
		Tunnel segment steel bar stress
		Tunnel ring ovality
	Grouting	Grouting mix proportion
		Grouting amount
		Grouting pressure
		Slurry gelation time
		Slurry strength
	Soil discharge	Excavation face stability
		Pressure chamber pressure
		Shield rotation angle
		Blade wear
		Blade rotation speed and torque
		Soil discharge amount
	Waterproofing	Segment impermeability
		Crack maximum width
		Water leakage amount
		Drainage capacity

Table 6: limitations and corresponding accidents of risk precursors in shield tunnel construction.

Risk precursors (monitorable)	Limitations	Risk accidents
Enclosure wall top displacement (mm)	30	Collapse
Enclosure wall maximum displacement	50	
Ground settlement	30	
Reinforcement soil compressive strength	Design value	Collapse/Flood
Shield axis deviance	50	
tunnel ring ovality	±5‰D	
Segment position deviation	±50	
Excavation face stability factor	6	Collapse/Mechanical injury
Ground settlement above the pipeline	3	Collapse/Fire/Explosion/Poisoning
Ground cumulative settlement above the pipeline	10	

3.3. Risk accidents and solutions

Like risk precursors in section 0, this paper summarizes risk accidents and their solutions in shield tunnel construction based on related researches, as shown in Table .

It is worth noting that many researches considered some risk factors (e.g. shield mechanical failure) and some risk precursors (e.g. shield axis deviation) as risk accidents. But according to the classification criteria of three risk elements in this paper, they are not. So, the risk accidents given in this paper have filtered the unsatisfied elements.

Table 7: risk accidents and solutions in shield tunnel construction.

Construction	Risk accidents	Solutions
Shaft excavation	Foundation pit stability	Foundation pit precipitation
		Excavation support
		Enhance monitoring
Shield enter/exit	Shield forehead sink	Shield gesture adjustment
		Launch end elevation raising
Shield excavation	Excavation face stability	Control face support pressure
		Balance soil excavation and discharge
		Control excavation speed
		Enhance monitoring
	Ground collapse	Enhance waterproofing

	Balance soil excavation and discharge
	Increase grouting amount
	Change blade
	Enhance monitoring
Tunnel floating	Shield gesture adjustment
	Increase grouting amount
	Enhance monitoring
Explosion/Poisoning	Enhance ventilation

3.4. Example relationships between risk factors, precursors, and accidents

After collecting instances of risk factors, precursors, and accidents, Fig. 2 gives example relationships between them based on the relationships proposed in Fig. 2.

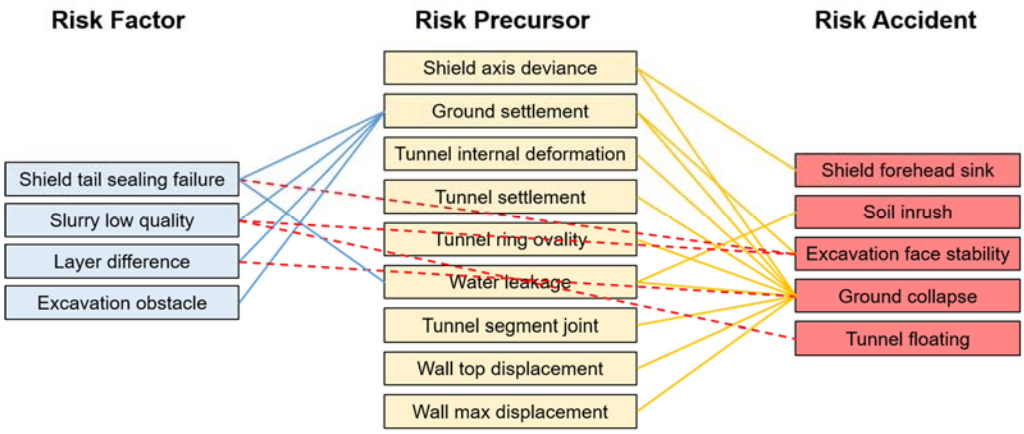


Fig. 2: example relationships between risk factors, precursors, and accidents.

4. ONTOLOGY DEVELOPMENT

As a recommended standard for W3C and a widely used ontology language, the Web Ontology Language (OWL) is designed to provide a common way to handle the content of Web information and be read by computer applications. However, the readability of OWL is not friendly to human, so a software is generally required for construction, storage, reasoning, and query of ontology. In this paper, we choose Protégé to develop the ontology of shield tunnel construction, which is an open source software developed by Stanford University (https://protege.stanford.edu/).

4.1. Definition of classes and properties

The core concepts in shield tunnel construction includes: Construction Method, Risk (Risk Factor, Risk Precursor, Risk Accident), and Solution. In order to make the ontology more suitable for engineering such as expressing the order and hierarchy of construction methods, this paper adds two concepts: Project and Task. In ontology, concepts are expressed by classes, so this paper builds 7 classes according to the above 7 concepts.

Relationships between classes are expressed by properties. Ontology divides property into object property and datatype property, while the former connects two objects and the latter connects object and built-in datatype. As for object properties, *hasPrecursor* links *ConstructionMethod* to *RiskPrecursor*, and *hasPrecursorAccident* links *RiskPrecursor* to *RiskAccident*. In addition, this paper defines datatype properties *hasPrecursorValue* and *hasPrecursorLimit* for *RiskPrecursor* class. These two properties denote the actual monitored value and upper limit of *RiskPrecursor* respectively, and once the monitored value exceeds the upper limit, the corresponding *RiskAccident* will be triggered.

Fig. 3 shows all classes and some of their properties in the ontology. In Fig. 3, rectangles represent classes, rounded rectangles represent built-in datatypes, blue/green lines means object/datatype properties.

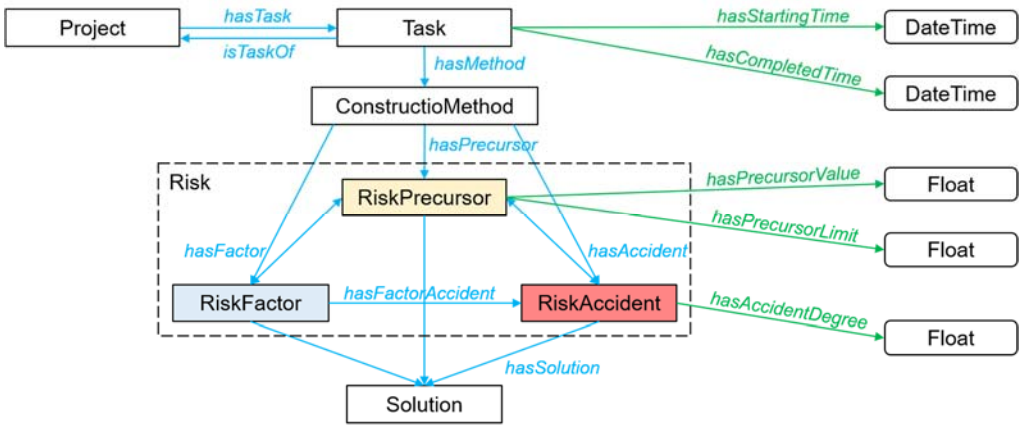


Fig. 3: classes and some of their properties in the ontology.

4.2. Developing ontology in Protégé

Fig. 4 shows the screenshots of classes and properties in Protégé. In Figure 5a, *ShaftExcavationMethod* is a sub-class of *ConstructionMethod*, and it is connected to three sub-classes of *RiskPrecursor* by the property *hasPrecursor*, such as *hasPrecursor some GroundSettlementPrecursor*. It does not intersect with any other sibling class, so there is a *Disjoint with* statement, and it has two instances.

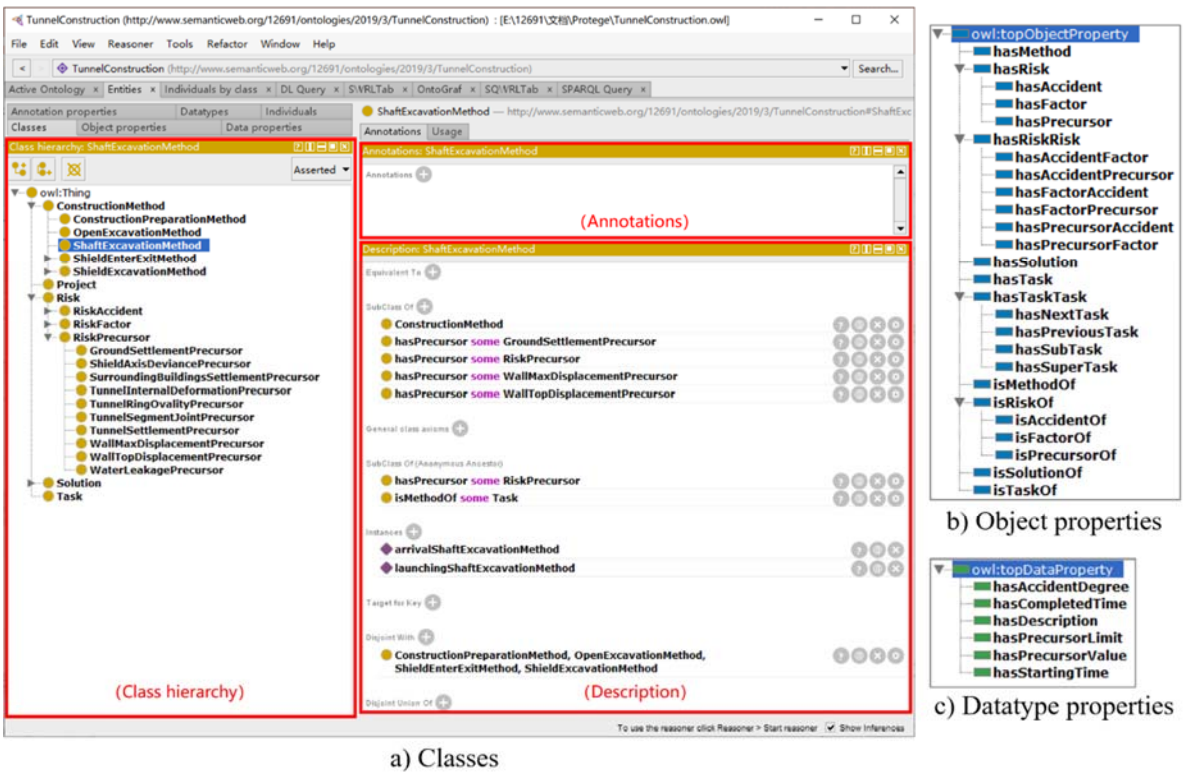


Fig. 4: screenshots of classes and properties in Protégé.

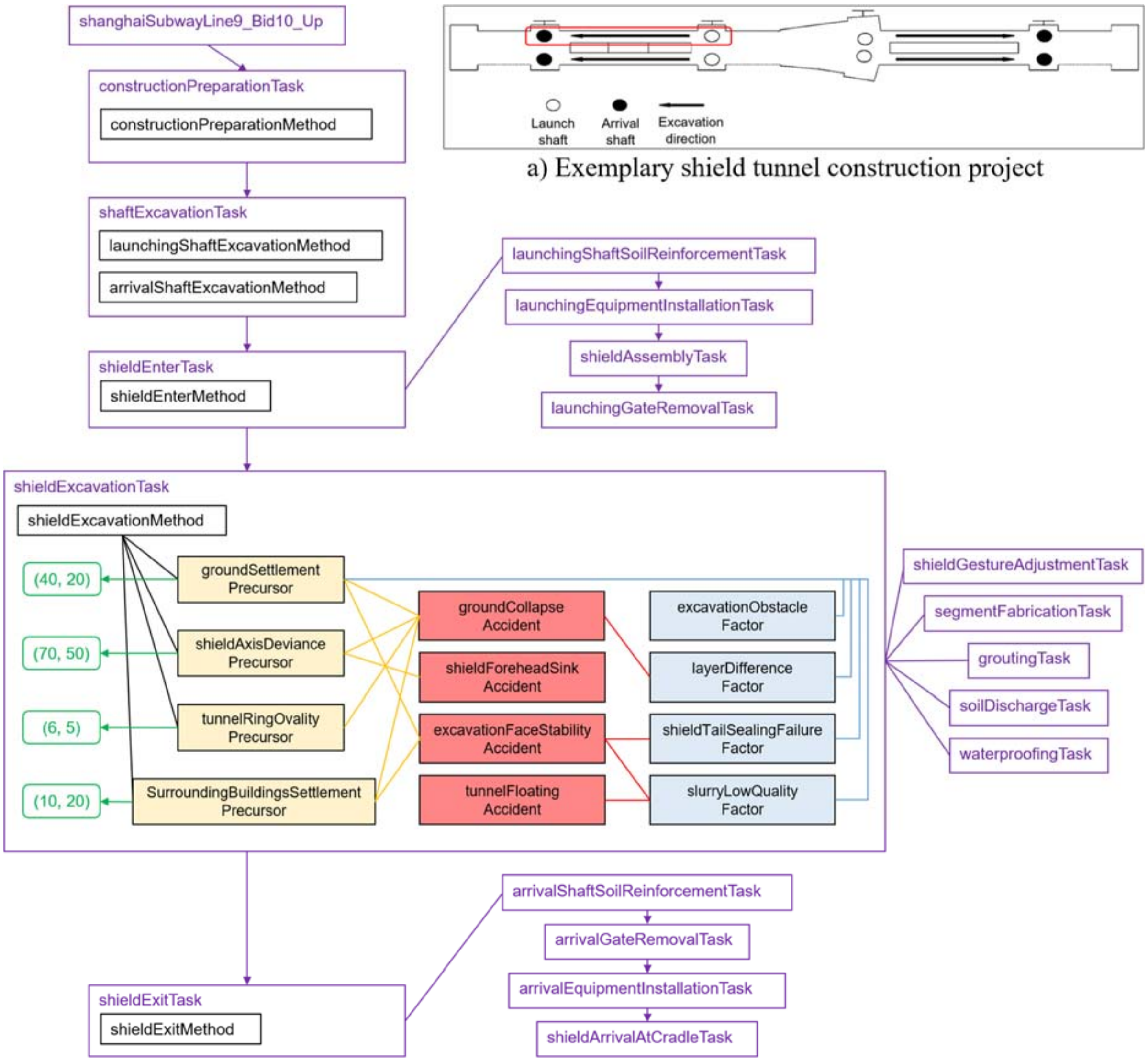
In Figure 5b, some properties are sub-properties of another property, such as *hasPrecursor* is a sub-property of *hasRisk*. In this condition, the sub-property's range is sub-class of the super-property's range, which can facilitate reasons and queries in the ontology. Besides, some properties are inverse of another property, such as *hasPrecusor* and *isPrecursorOf*, which means the domain (range) of *hasPrecursor* is range (domain) of *isPrecursorOf*.

5. DEMONSTRATION

5.1. Create instances

Classes stored in an ontology are conceptual and abstract, while actual projects are concrete. To use the ontology to express actual projects, we need to create instances of corresponding classes. In this paper, we create instances to express constructions and risks of a project, and identify risks through query in ontology. Fig. 5 a shows the exemplary shield tunnel construction project, which is a part of Shanghai subway Line 9 (the red box shows the selected construction section).

This paper selects the shield enter, shield exit, and shied excavation tasks in this project for further research in detail, and only represents risks in shield excavation task for simplicity. Fig. 5 b shows all created instances. In this figure, purple rectangles denote *Project* or *Task*, while black rectangles denote *ConstructionMethod*. In *ShieldExcavationTask*, *RiskFactor/Precursor/Accident* have colorful background, and green rounded rectangles means the (*hasPrecursorValue*, *hasPrecursorLimit*) of *RiskPrecursor*.



a) Exemplary shield tunnel construction project

b) Instances to represent the exemplary project

Fig. 5: the exemplary shield tunnel construction project and instances to represent it.

5.2. Semantic query in typical scenarios

This paper uses SPARQL Protocol and RDF Query Language (SPARQL) to query risks and their solutions in the exemplary project. SPARQL is a set of W3C Recommendations that provide language and protocols for querying and processing RDF content.

The contents to be query are: *RiskPrecursors* which satisfy *hasPrecursorValue* >= *hasPrecursorLimit*, and their corresponding *RiskAccidents* and *Solutions*. The query is implemented twice, the first for satisfied *RiskPrecursors* and *RiskAccidents*, while the last for the *Solutions*. The code of the first query is show in Fig. 6 (prefix part has been omitted). Note that the code of the last query only needs to change `SELECT DISTINCT ?m ?p ?pv ?pl ?a ?ad` to `SELECT DISTINCT ?a ?S.` The results of two queries are shown in Table and Table .

```
SELECT  DISTINCT  ?m ?p ?pv ?pl ?a ?ad
WHERE {
?M rdfs:subClassOf :ConstructionMethod.
?m a ?M.

?P rdfs:subClassOf :RiskPrecursor.
?p a ?P.
?p :isPrecursorOf ?m.
?p :hasPrecursorValue ?pv.
?p :hasPrecursorLimit ?pl.
?A rdfs:subClassOf :RiskAccident, ?rs.
?a a ?A.
?a :hasAccidentDegree ?ad.
?p :hasPrecursorAccident ?a.

?S rdfs:subClassOf :Solution.
?rs a owl:Restriction.
?rs owl:onProperty :hasSolution;
owl:someValuesFrom ?S.
FILTER (?pv >= ?pl) }
order by  (?p) desc (?ad)
```

Fig. 6: the code of query for satisfied *RiskPrecursors* and *RiskAccidents.*

Table 8: the first query result (*RiskPrecursors* and *RiskAccidents*)

m (ConstructionMethod)	*p (RiskPrecursor)*	*pv**	*pl**	*a (RiskAccident)*	*ad**
shieldExcavationMethod	*groundSettlementPrecursor*	40	20	*groundCollapseAccident*	1
				excavationFaceStabilityAccident	0.6
	shieldAxisDeviancePrecursor	70	50	*groundCollapseAccident*	1
				shieldForeheadSinkAccident	0.4
	tunnelRingOvalityPrecursor	6	5	*groundCollapseAccident*	1

* pv/pl means *hasPrecursorValue*/*hasPrecursorLimit* of corresponding *RiskPrecursors*; and ad means *hasAccidentDegree* of *RiskAccidents*

Table 9: the last query result (*Solutions*)

a (RiskAccident)	*S (Solution)*
groundCollapseAccident	*EnhanceWaterproofSolution*
	IncreaseGroutingAmountSolution
	ChangeCutterSolution
	ControlFaceSupportPressureSolution
	BalanceSoilExcavationAndDischargeSolution
	EnhanceMonitoringSolution
excavationFaceStabilityAccident	*ControlFaceSupportPressureSolution*
	ControlExcavationSpeedSolution
	EnhanceMonitoringSolution
	BalanceSoilExcavationAndDischargeSolution
shieldForeheadSinkAccident	*LaunchEndElevationRaisingSolution*
	ShieldGestureAdjustmentSolution

The query results show that all *RiskPrecursors* which satisfy the requirement are correctly queried and *Solutions* are given for each *RiskAccident*. For example, the *shieldAxisDeviancePrecursor* exceeds the limit (70 > 50); and the triggered *RiskAccidents* are: *groundCollapseAccident*, *shieldForeheadSinkAccident*; and the *Solutions* are: *IncreaseGroutingAmountSolution*, *ControlFaceSupportPressureSolution*, *ShieldGestureAdjustmentSolution*, etc.

6. CONCLUSION

This paper develops an ontology of shield tunnel construction according to the result of WBS and risk analysis and finally applies it. In the WBS of shield tunnel construction, this paper divides the construction into five categories: Construction Preparation, Shaft Excavation, Shield Enter/Exit, Shield Excavation, and Engineering Acceptance, and then decompose each of these categories to obtain the WBS second level of the shield tunnel construction. In the risk analysis, this paper proposes the concept and relationships of three risk elements, namely, risk factor, risk accident, and risk precursor, and gives detailed examples of each risk element and their relationships in shield construction. The ontology proposed by this paper eliminates some shortcomings in existing ontologies, which enables the solution can be represented in ontology instead of SWRL and the construction order and hierarchy can be expressed. The application results show that the ontology can help identify the risks in shield tunnel construction and give corresponding solutions, which can provide a guidance for construction safety.

The advantages of using ontology for risk assessment and solutions are that it makes knowledge to be: (1) stored and expressed in a more organized way; and (2) shared and reused with high convenience. The first advantage can enhance the efficiency and semantics of information retrieval compared to traditional knowledge management methods such as databases and literal records. In addition, ontology makes it possible to create a new knowledge base with existing knowledge bases, which facilitate the building of knowledge base to achieve higher level of detail and broader range of scope.

It is worth noting that, deficiencies still exit in the ontology developed in this paper. For example, *RiskAccidents* can only be triggered by single *RiskPrecursor* but not a combination of *RiskPrecursors*, and the same *RiskAccident* triggered by different *RiskPrecursors* may have different *Solutions* are also not considered, which can be further researched by future works.

7. ACKNOWLEDGEMENT

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Schedule and Cost Management

Evaluating the Economic and Social Benefits of Multi-utility Tunnel Through an Agent-based Simulation Approach

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ABSTRACT: *Multi-utility tunnel (MUT) is one potential approach to achieve urban sustainability. As such, many studies have been conducted to prove the advantages of MUT over traditional open-cut method (OC). However, these studies focus on investigating economic cost whereas other aspects, such as social impact is not well addressed in quantitative manner. Hence, this paper aims to improve existing studies by quantifying a critical part of social cost of utilities placement, i.e., traveller loss caused by repeated excavations and reinstatements (E&R) in urban road network. For this purpose, an agent-based model (ABM) that addresses unique attributes and actions of vehicles and interactions between vehicles and the network, is developed to estimate the traveller loss, which is then integrated with economic cost to compute and compare the life-cycle cost (LCC) of MUT and OC. The proposed ABM is tested in a MUT project in Shanghai, China, and the results indicate that: 1) E&Rs due to adoption of OC result in severe traffic congestion, leading to substantial traveller loss; 2) when traveller loss is not included in LCC estimation, OC has a lower LCC in most scenarios; and 3) when traveller loss is included, the time it takes coverage the LCCs of MUT and OC is largely reduced, and MUT demonstrates great value in terms of significantly lower LCC than OC. Therefore, it can be concluded that when social impact is considered, MUT will bring more long-term benefits than OC in urban road networks. Besides, the proposed approach provides a new way to quantify social cost of underground utilities thus has the potential to assist decision-making in terms of selecting utilities placement methods.*

KEYWORDS: Multi-utility Tunnel; agent-based simulation; sustainability; life-cycle cost.

1. INTRODUCTION

These instructions are intended to guide authors when preparing the abstract for the 8th International Conference on Sustainability is a critical goal of modern city construction and multi-utility tunnel (MUT) has been recognised as an essential approach to gain urban sustainability (Hunt et al., 2016). MUT is a subsurface infrastructure containing many utilities (e.g., gas, power, water and sewer). Unlike conventional utilities placement methods, such as open-cut (OC), MUT houses utilities in a tunnel and provides access for workers and equipment to any point of its length (Canto-Perello et al., 2013). MUT can significantly improve urban sustainability because it minimises repeated excavations and reinstatements (E&R) on roads for operations on underground utilities, thus the associated disturbance, e.g., traffic congestion, is largely avoided. However, the initial cost of MUT is considerably higher than the OC and benefits of MUT are still difficult to be quantified (Broere, 2016). As such, the decision making of selecting MUT or OC has become a research topic that gains increasing attention (Hunt et al., 2014, Canto-Perello et al., 2016). Despite that various criteria are covered in these studies for selection, only economic benefit of MUT is quantified, whereas other indicators, such as those in the social and environment aspects, remain qualitative.

At the same time, urban traffic is getting increasingly congested and road interruption caused by operations on utilities has been regarded as one major social impact of underground utilities (de Jong and Bliemer, 2015). As such, studies were conducted to monetise the negative effect of traffic interruption due to road E&R for underground utilities (Jung and Sinha, 2007, Ariaratnam and Sihabuddin, 2009). However, these studies have limitations. For one thing, many studies compute costs of one-off E&R in the construction stage only, but do not consider the cost due to multiple E&Rs in the life-cycle of utilities for maintenance (Hunt et al., 2014). For another, a traffic network is a complex system where vehicles, have unique attributes and actions rules with which they interact and make decisions. The actions and interactions of vehicles can affect traffic conditions and in turn, the effect of road interruptions, but they are not included in current studies of traveller delay estimation (Chen and Cheng, 2010). Nevertheless, these studies provide insights to embed vehicle attributes (e.g., destination and departure time) and model their actions and interactions in ABM, as well as approaches to evaluate the performance of a transportation system. As such, they make the development of an ABM model which integrates social and economic cost of constructing underground utilities feasible.

Hence, the study applies agent-based modelling (ABM) to address the complex and dynamic behaviours of vehicles in a CBD network, which are used to estimate the traveller delays when MUT and the OC is adopted. The delay is monetised and integrated with the economic cost to estimate the LCC of the two methods, which is a common indicator to make decisions regarding underground utilities (Hunt et al., 2011, Canto-Perello et al., 2016). As such, the benefits of MUT, in both economic and social terms, are better demonstrated, which can facilitate informed decision makings on selecting utilities placement methods for urban planners.

2. BACKGROUND

2.1. Decision Making on Selecting MUT or OC

The OC buries utilities in the soil while MUT hosts utilities and the auxiliary system in a tunnel. The main advantages of MUT come from the elimination of E&R, which can reduce maintenance cost, extend road service life, and minimise pollution and traffic congestion. The main advantages of OC include low initial cost, short construction period, and clear liability and risk distribution (Canto-Perello et al., 2013). As such, existing studies of decision making on selecting utilities placement methods are based on the pros and cons of MUT and OC, and can be generally divided into quantitative and qualitative group.

Qualitative studies aim to establish an index system, covering indicators in economic, social and environment aspects. Usually, a score and a weight which is usually obtained from experts, are assigned to each indicator. These weighted indicators are aggregated with their quantitative counterparts, e.g., cost, as indexes for decision making. Common ways for indicators integration include Analytic Hierarchy Process (AHP) and Delphi technique. There are also ways to support decision making, such as the ELECTRE multi-criteria decision-making method and SWOT analysis. Nevertheless, these studies are subjective and based on prior experience (Koo et al., 2009, Canto-Perello et al., 2016).

Quantitative studies investigate the quantified cost of MUT and OC, and this branch starts from economic cost estimation. For instance, Li et al. (2019) conducted a cost analysis of installing electrical cables in MUT, and showed MUT was more economically sustainable than cable trench. Hunt et al. (2014) computed the LCC of MUT and OC, considering the economic cost of E&Rs, and indicated substantial long-term cost saving of MUT. However, it is still difficult to monetise social impact, such as traffic congestion, security, and liability. Nevertheless, existing studies focus on quantifying social impact of traffic congestion, by estimating traveller delay, and its monetised term, traveller loss. For instance, Tighe et al. (1999) evaluated traveller loss by multiplying the hourly wage of drivers with additional travel time. Jung and Sinha (2007) and Matthews et al. (2015) developed a set of linear equations to calculate traveller loss caused by slowing and queuing. However, these studies ignore the repetitive E&Rs in the entire lifespan, and they do not consider the attributes and dynamic interactions of vehicles.

2.2. Agent-based Modelling and Applications

ABM is a computer simulation approach aiming to describe a system using its constituent units. The attributes of agents and their actions and interactions are defined, then macroscopic system behaviours are generated from the myriad interactions among agents. It is believed that ABM is suitable for studying complex adaptive systems such as transportation (Bazzan and Klugl, 2014) xxx. One major application of ABM in transportation is to improve transportation performance, including reducing congestion. For instance, Zheng et al. (2012) utilised ABM to test the effect of congestion pricing schemes in terms of balancing traffic demand; Huynh et al. (2014) estimated the traffic density on a CBD road network and trip distribution of urban dwellers to predict future traffic demands.

These studies provide approaches to embed vehicle attributes (e.g., destination and departure time) and model their actions and interactions in ABM. As such, they are useful to assist development of the ABM model in this study.

Thus, this paper aim to develop an ABM model to compare the degree of traffic congestion due to E&Rs in the lifespan of MUT and OC projects, considering complex and dynamic behaviours of vehicles, then estimate the traveller loss caused by congestion as the social cost of utilities placement, and finally embed the social cost in the LCC comparison between MUT and the OC.

3. METHODS

3.1. ABM model Development

3.1.1. Parameters Setting of Agents

In this study, there are two agent groups, i.e. vehicles and a network. Two simulation scenarios are setup for the MUT (i.e. no road interruption) and the OC (i.e., there are periodic road interruptions due to E&R). For effective simulation, parameters for ABM should be determined. Based on literature of traveller loss estimation and ABM application in transportation sector, Table 1-3 list the selected parameters.

Table 1: Parameters of car agents.

Parameter name	Unit	Description
Average normal velocity	km/hour	The average speed in normal condition
Acceleration/deceleration	m2/s	The acceleration and deceleration rate
Average income	dollars/hour	Hourly income of the driver
Stay Possibility	%	The possibility if a car stays in a network after entering
Entrance	N/A	The point that a car enters a network
Exit	N/A	The point that a car leaves a network
Destination	N/A	The final stop point of a car after entering a network
Entering routes	N/A	Routes for a car to move from an entrance to a destination
Leaving routes	N/A	Routes for a car to leave a network
Duration of stay	hour	The duration that a car stays in a network
Optimism level	%	The possibility that a car takes detour in case of road interruption

Table 2: Parameters of the network agent.

Parameter name	Unit	Description
Segment length	m	Length of a single road segment
Width of lane	m	The width of a single lane
Lane capacity	pcu/hour/lane	The maximum number of cars per hour a single lane can carry
Number of lanes	N/A	The number of lanes of a road
Entrance traffic	pcu	The number of cars arriving at an entrance
Traffic control plan	N/A	The plan that can change traffic flow during E&R
Network layout	N/A	The layout of roads, the streamline design, and locations of entrances
Travel schedule	N/A	The density function reflecting variance of the number of cars appearing at an entrance

Table 3: Parameters for LCC estimation of MUT and OC.

Parameter name	Unit
Construction and Maintenance cost of MUT	$/m
Construction and Maintenance cost of OC	$/m
Social discount rate	%
Increasing rate of drivers' income	%
Increasing rate of maintenance costs	%

Three methods are adopted to obtain parameters. First, databases, reports and surveys were searched to collect values of general parameters that do not depend on specific projects, such as average vehicle speed and income of drivers. Second, the authors approached agencies of local planning, to acquire detailed data, such as road geometrical, lane capacity, streamline design, traffic volumes, and information relating to attributes of vehicles, such as travel schedule. Finally, some parameter values are not collected but computed during simulation.

3.1.2. Action Rules of Vehicle agents

The most important action of vehicles is route selection (de Jong and Bliemer 2015). A route can be represented by a set of stop points. A stop point is defined as network entrance, intersection of road segments or any specified point along a segment. A route can then be described by assigning a unique order of stop points, considering the streamline design. At network level, route selection can be divided into entering, leaving and detour route selection.

Entering route selection: When a vehicle arrives at an entrance, it evaluates if it will stay in the network. If not, another entrance is selected, to which the vehicle drives and leaves. Otherwise, a stop point is selected as the destination. The shortest route to reach the destination is identified by comparing the absolute distance of routes using segment geometrical data.

Leaving route selection: This action only applies to vehicles stay in a network. When a vehicle arrives at its destination in a network, the duration of stay is estimated, which depends on the purpose of travel and the time of arrival. Then, an exit is selected as a new destination for the staying vehicle, with more weights given to the original entrance.

Detour selection: This action applies when interruptions happen along a route. Specifically, a vehicle checks all stop points on the selected route. If there is any stop point located in interrupted segments, the vehicle must decide whether to take a detour to avoid interruption. The possibility to take detour can depend on the optimism level, i.e., a driver who is willing to take risk will be more likely to stay in the original route (Fujii, Uchida et al. 2017).

3.1.3. Action Rules of the Network Agent

The road network is a single agent and has three actions: 1) generates vehicles; 2) if OC is adopted, periodically triggers E&Rs and implements traffic control plan; 3) records network performance.

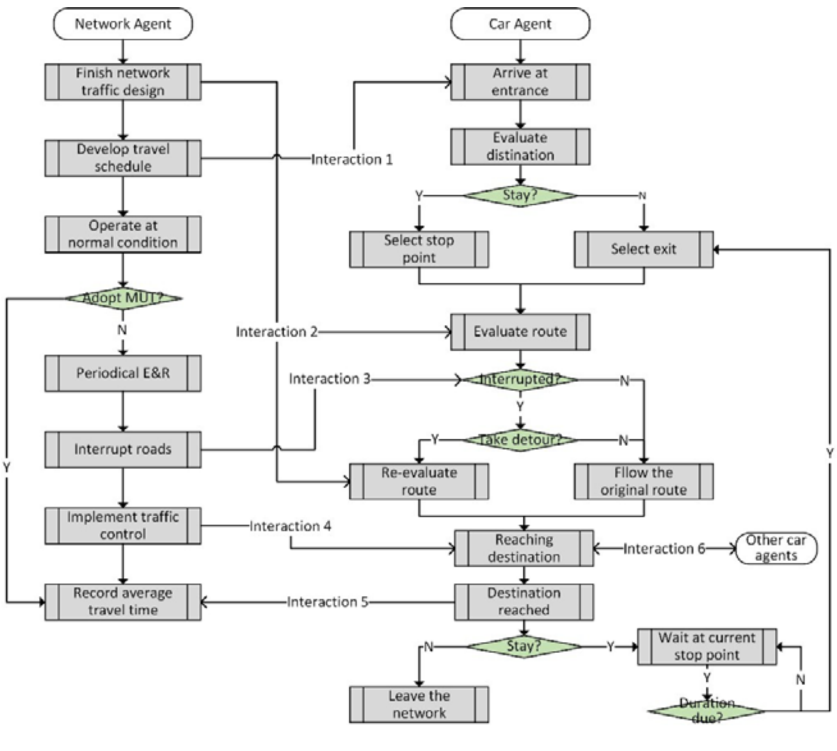

Fig. 1: Actions and Interactions Rules between Agents.

Vehicle generation: The vehicles generation pattern depends on a travel schedule, which defines the number of vehicles arriving at each entrance at different hours. This vehicle generation process can be realised using Eq. 1.

$$T_{kj} = T^{*}(j) \times T_{k} \qquad \text{(Eq. 1)}$$

Where T_{kj} is the traffic volume at entrance k at hour j; and $T^{*}(j)$ is the distribution function that returns the proportion of vehicles arriving at entrance k at hour j, which is obtained by referring to surveys conducted by local authorities (USDT, 2018).

Traffic control plan implementation: To perform E&R activities, traffic control plans should be established. The half-block (i.e., one lane is closed and vehicles take turns to use the un-blocked lane) is adopted in this study, which is suitable for typical two-lane roads.

Network performance recording: One critical performance indicator for this study is the travel time, i.e., the time gap between a vehicle enters and leaves, which is the basis to estimate traveller loss. Thus, the network agent periodically records the travel time of each vehicle, using Eq. 2.

$$T_i = L_i - E_i - S_i \times D_i \quad \text{(Eq. 2)}$$

where T_i, L_i, E_i and D_i represent travel time, leaving time, entry time and duration of staying of i, respectively, and S_i is a binary variable that equals 1 if vehicle i stays, and 0 otherwise.

3.1.4. Interaction between Vehicles and Road Network

The action rules of agents and interactions between agents are shown in Fig. 1. There are six types of interactions where five happen between vehicles and the network while the remaining one happens between vehicles. The arrow in Fig. 2 indicates the direction of data flow.

Specifically, through interaction 1, vehicles read the travel schedule to determine the entrance and the timing of appearance. Interaction 2 refers to the route selection actions. Interaction 3 allows vehicles to evaluate the road condition and the detour action. Interaction 4 affects vehicles via traffic control plans, such as forcing vehicles to queue. Interaction 5 allows the network to record network performance indicators. Interaction 6 includes typical interactions of vehicles, such as acceleration, deceleration, overtaking, and lane changing.

3.2. Traveller Loss Evaluation

where TL is traveller loss from one E&R activity, T_{avg} is the average travel time under normal conditions, d is the number of days that one E&R lasts, m is the number of vehicles in day j, T_i and I_i represent the travel time and average hourly income of vehicle i, respectively. Furthermore, if the lifespan of the utilities is known, the net present value of traveller loss is estimated using Eq. 4. where L is the number of years in the lifespan, f_i is the failure frequency at year i, i.e. the number of maintenance activities (E&Rs) in year i, r_0 is the economic discount rate, and r_1 is the increasing rate of divers' income.

$$TL = \sum_{j=1}^{d} \sum_{i=1}^{m} I_i \times (T_i - T_{avg}) \quad \text{(Eq. 3)}$$

$$NPV_{TL} = \sum_{i=1}^{L} f_i \times TL \times (1 + r_1)^i \Big/ (1 + r_0)^i \quad \text{(Eq. 4)}$$

3.3. Life-cycle Cost Comparison

LCC analysis is conducted for MUT and OC, based on the model in a previous study (Hunt et al., 2014). The key is to find a tipping point, i.e., the number of years it takes for the LCC of MUT and OC to converge. If MUT can eliminate E&R, a tipping point is solved using Eq. 5.

$$DC_{OC} + \sum_{i=1}^{T} \left(\frac{\sum_{k=1}^{f_i} n_k \times MC_{OC} \times (1+r_2)^i}{(1+r_0)^i}\right) + NPV_{TL} = DC_{MUT} + \sum_{i=1}^{T} \left(\frac{AMC_{MUT} \times (1+r_2)^i}{(1+r_0)^i}\right) \quad \text{(Eq. 5)}$$

where T is the number of years to reach a tipping point, DC_{MUT} and DC_{DB} are the direct construction costs of the two methods, MC_{DB} is the average maintenance costs of a single utility placed by the open cut method; AC_{MUT} is the annual maintenance costs of the MUT, n_k is the number of failed utilities in the k^{th} E&R activity at year i, and r_2 is the increasing rate of maintenance costs considering cost variances of labour, materials, and equipment.

4. CASE STUDY

The MUT project in the West Bund Media Port (WBMP) of Shanghai, China was selected as a case study. The total length of the MUT is 880m and Fig. 2 shows the layout of the project.

For simplification, it is assumed that: 1) all vehicles have similar shape; 2) cars staying in the WBMP only leave after the pre-defined duration; 3) half-block control plan is adopted, with a cycle time of 10 minutes (Lin et al., 2013); and 4) the social discount rate, increasing rate of income, and increasing rate of maintenance costs are 8.0%, 8.9%, and 6.8%, respectively.

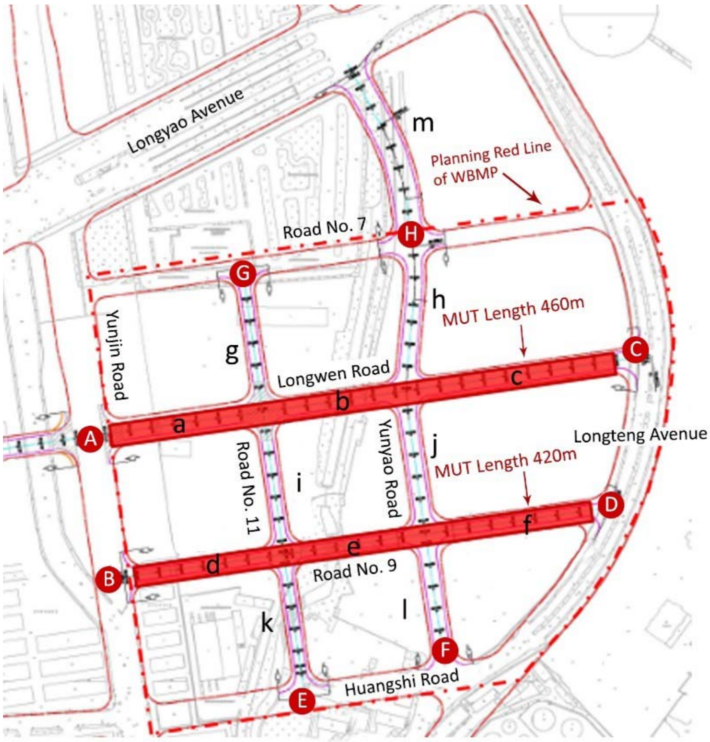

Fig. 2: Layout of the MUT project

4.1. Data Collection

Following the methods introduced in Section 3, Table 4-7 below illustrate data collection results. Table 4: Traffic volume of entrances of WBMP

Table 4: Traffic volume of entrances of WBMP

Entrance	Orientation	Weekday 12 hours' traffic	Peak hour traffic volume
A	W - E	3067	280
B	W - E	3200	290
C	E - W	4667	420
D	E - W	5067	360
E	S - N	2667	250
F	S - N	2470	240
G	N - S	3333	240
H	N - S	3200	290

Table 5: Attributes relating to cars and drivers

Parameters	Unit	Value
Normal average speed	km/hour	T (35, 60, 50)
Acceleration rate	m/s2	N (1.8, 0.1)
Deceleration rate	m/s2	N (4.2, 0.2)
Average hourly income	dollars	N (8.5, 1.5)
Optimism level	%	T (10%, 30%, 20%)
Duration of staying	hour	T(1, 4, 2)
Duration of E&R	days	T (1, 5, 3)

Table 6: Cost composition of OC

Parameters of cost item	Size/Specification	Cost ($/m/utility)	No. of utilities	Material
Water supply pipe	DN200	80.0	6	cast iron
Gas supply pipe	DN300	120.0	3	cast iron
Drain pipe	DN1350	447.0	2	cast iron
Sewer pipe	DN200	100.0	6	asbestos cement
Electricity trench	2x5, 2x8, 2x10	485.0	1	PVC
Communication trench	1x12	152.0	1	PVC

Table 7: Cost composition of MUT maintenance

Cost stage	Parameters of cost item	Unit cost ($/m)
Construction	MUT construction (including auxiliary system)	8955.0
Maintenance	Water	18.4
	Gas	15.0
	Drain	34.0
	Sewer	13.0
	Electricity	14.4
	Communication	8.0
	Structure	85.0
	Auxiliary system	160.0

4.2. Traveller Loss Calculation

Fig. 3 illustrates the network performance of WBMP by demonstrating the average traffic density in morning peak hours (i.e., 6 am - 10 am), which is computed by dividing the number of cars on a lane by the lane capacity. The segment coloured by green indicates smooth traffic flow (average speed > 50 km/h) and segments coloured by red indicate serious congestion (average speed < 10km/h). If MUT is adopted (Fig. 3(a)), most segments remain green. However, if OC is adopted (Fig. 3(b)), severe congestions happen on several segments under which utilities are buried, and their adjacent segments also suffer moderate congestion (coloured in orange or yellow).3D scenarios are given in Fig. 3 to visualise queueing cars when E&R happens and the smooth traffic in normal condition.

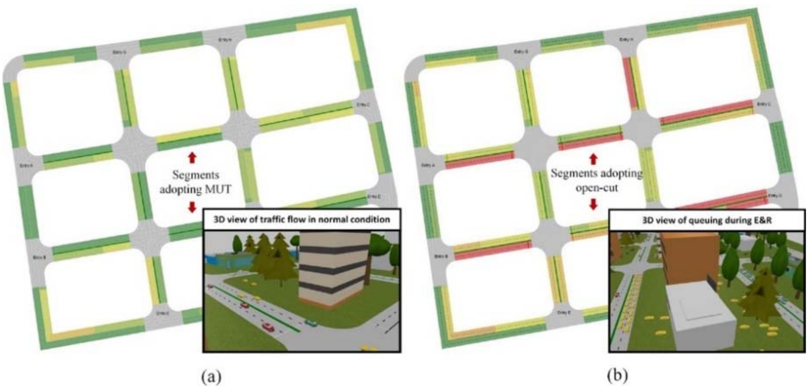

Fig. 3: Average Traffic Density Map (a) Normal condition (b) Congestion due to E&R

Furthermore, Fig. 4 illustrates the network performance in morning peak hours. It turns out that the average travel time when OC is adopted is eight times than that of MUT. Besides, there is a larger variance of travel time in the OC scenario. On the other hand, the average speed of cars declines from 34.52 km/hr to 28.09 km/hr due to E&R activity. Again, when OC is adopted, the average speed again presents larger variance due to frequent acceleration and deceleration in congested areas.

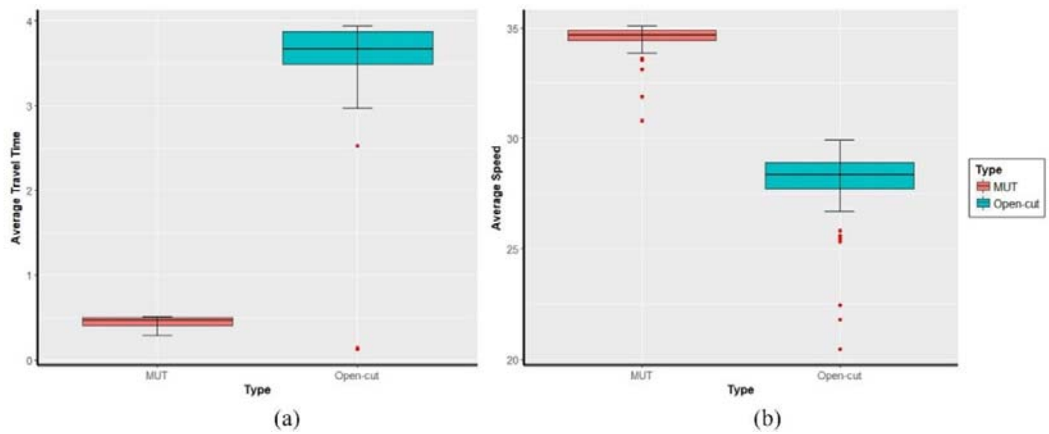

Fig. 4: Network Performance (a) Average travel time (b) Average car speed

4.3. LCC Comparison between MUT and OC Scenario

In this study, the failure frequency (i.e., the frequency of E&R) is changed while other variables remain the same. Fig. 5 shows if traveller loss is not considered, the LCC of OC is lower than MUT if n is less than 3, and it can take 45.37 years to reach a tipping point. However, as shown in Fig. 6, when traveller loss is included, there is a tp at year 26.39 when f=1. When n is 3, tp can be found at 13.80, 9.35, 7.16, and 5.87 years, respectively. In the extreme scenario, i.e., f=3, the LCC of OC is about 4.4 times than that of MUT. The results indicate that the LCC of MUT, considering economic and social aspects, can be much less than that of OC, despite of the small project scale. Another finding is that the most significant reduction of tp happens when f increases from 0.5 to 1. As f increases, the LCC curve of MUT remain almost unchanged. This suggests that a high f is not a must to realise benefits MUT in terms of traveller loss saving. In addition, due to the increase rate of traveller's income and maintenance cost, the LCC of OC increases exponentially, increasing the gap of LCCs between MUT and OC. It shows that as the lifespan of utilities increase, the long-term benefit that MUT can bring also increases. Nevertheless, the results show that once traveller loss is included in LCC, the number of years it takes to reach the tipping point is considerably reduced, indicating more benefits can be reaped by MUT in a long run.

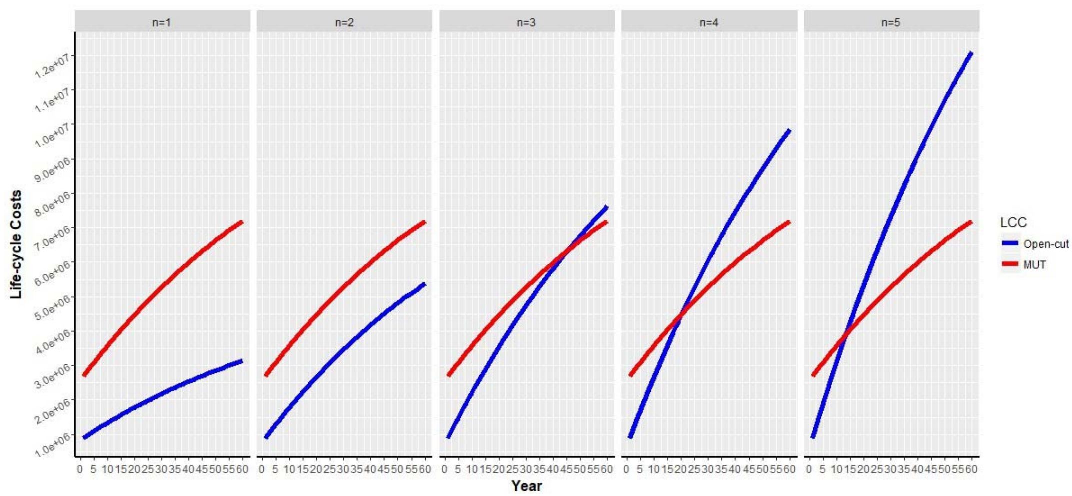

Fig. 5: LCC of MUT and open-cut when traveller loss is not included

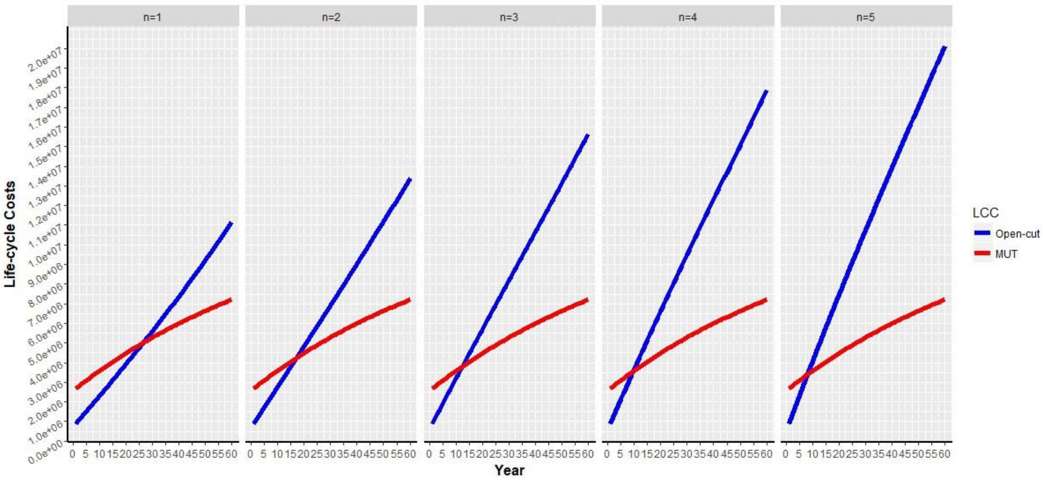

Fig. 6: LCC of MUT and open-cut when traveller loss is included

5. CONCLUSION

To this end, it can be argued there are four contributions of the study. First, previous studies that compare utilities placement methods usually evaluate economic indicators only. The proposed approach however, can quantify and integrate the social cost of MUT and OC in LCC estimation. Second, the traveller loss estimation is more objective using ABM, because the ABM allows flexible settings of attributes and actions of agents and enabling equations to be embedded to calculate individual and system performance, which improves the traditional traveller loss estimation by integrating knowledge of utilities placement and traffic control, meanwhile extending the knowledge by considering interactions between cars and between cars and the network. Third, existing studies treat utilities as linear components whereas LCC estimation in this paper is based on network thinking. Hence, the approach can include network factors, such as relationships of roads, network traffic streamline design and options of cars, all of which can affect traveller loss thus produce a more reliable estimation. Finally, the ABM approach can support decision-making. Many local governments do not have an objective way to choose utilities placement methods and the implementation of MUT is usually denied in practice because the long payback period masks the long-term economic saving. However, this study addresses both economic and social cost to shorten the payback period and improve the decision-making. For instance, a threshold (e.g., tp) can be set and if the ABM suggests a smaller tp than the threshold, MUT should be implemented.

In summary, this paper proposes an ABM approach to address the impact on both economic and social aspects to compare the LCC of MUT and OC, where the social impact is quantified by traveller loss. The results show that if the OC is adopted, E&R activities are periodically required and can result in severe road interruption and large amount of traveller loss. In contrast, the adoption of MUT can minimises the traveller loss. When such saving is incorporated in the LCC estimation, the number of years it takes to a point where the LCCs of MUT and OC converge is considerably reduced. In addition, traveller loss is merely a part of the social cost associated with the OC. If other social or environmental costs are included, the benefits of MUT are believed to be more evident. In summary, MUT has the potential to improve urban sustainability. Thus, the implementation of MUT should be encouraged, especially in regions with large traffic volume.

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Sustainability Construction and Management

Automatic Measurements of Carbon Emissions from Building Materials and Construction for Sustainable Structural Design of Tall Commercial Buildings

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ABSTRACT: *Tall buildings are large-scale civil infrastructures that consume substantial amounts of construction materials and cause significant environmental impacts such as embodied carbon emissions. Understanding the effect of structural design (such as materials and structural forms) on the embodied carbon of building materials and the carbon emissions from construction activities is important to improve the sustainability of tall buildings. This study, with reference to the life cycle assessment (LCA) approach, aims to measure the carbon emissions from construction activities and from major building materials in tall buildings in order to underpin the sustainable structural design of tall commercial buildings. The formulations for carbon measurement are proposed, taking into consideration the cradle-to-site carbon emissions from material production, on-site construction, and waste disposal and treatment, with application of locally or regionally specific emission factors. Next, an automatic measurement tool based on the proposed formulations is developed to evaluate the carbon emissions of a tall commercial building, One Taikoo Place, in Hong Kong. The choice of structural materials has critical effects on the structural behavior of the tall building, which in turn substantially impacts the amounts of material consumption and carbon emissions. This study provides deeper understandings and interesting insights into the carbon performance of tall buildings for different structural designs relevant to the Hong Kong built environment. The results also provide a basis for constructing more environmentally friendly and cost-efficient tall buildings, contributing to a sustainable built environment for mankind.*

KEYWORDS: embodied carbon, climate change, cradle-to-site, life cycle assessment, structural design, sustainable construction, tall buildings

1. INTRODUCTION

The construction industry is a vital sector in the world's economy, contributing to the economic growth and long-term development of many countries. Embodied carbon from buildings materials and carbon emissions from construction activities are seen as an increasingly important area in making buildings more environmentally sustainable and resource efficient (Gan et al, 2020). The carbon emissions from material production and construction activities account for 27% of a building's life cycle carbon emissions (Halcrow Yolles, 2010). Hence, reducing embodied carbon is important not only for reducing resources and associated costs but also mitigating longer-term risks from resource availability. Junnila and Horvath (2003) was an early attempt to measure the embodied carbon from building material production for a five-story office tower. Blengini (2009) evaluated the potential of carbon reduction due to the reuse and recycling of demolition wastes. Previous studies have been focused on the carbon emissions from the construction of low-rise residential houses or buildings with 20 to 30 stories in heights (Scheuer et al., 2003; Gustavsson et al., 2010). There are needs for case studies to demonstrate the relationship between the carbon emissions and structural design of tall buildings. In addition, the information regarding the embodied carbon of construction materials was available in the life cycle inventories including the Inventory of Carbon & Energy (Hammond et al., 2011). The international carbon auditing guidelines for the life cycle of a product or a process (such as ISO 14067:2018, PAS 2050:2011 and the Greenhouse Gas Protocol) were also available. However, the values of embodied carbon in the inventories and/or carbon auditing methods are region-specific because the fuel mix and raw material resources vary in different countries or regions. The previous studies in other regions may not be applied directly to Hong Kong's context, therefore a locally specific study is needed to quantify and mitigate the embodied carbon of building materials and carbon emissions from construction. In addition, there're many design factors affecting the embodied carbon of high-rise (such as material compositions), demonstrating the need of performing a pilot study for the carbon measurement of tall buildings.

Therefore, this paper presents the measurement of the embodied carbon from major buildings materials and carbon emissions from construction activities to underpin the sustainable structural design of tall buildings in the Hong Kong context. The formulations for cradle-to-site carbon measurement are presented, taking into account of the emissions from resource extraction, material manufacturing, transportation, on-site construction, waste disposal, sewage discharge and treatment. We made references to local publications and guidelines on carbon auditing, including the Guidelines to Account for and Report on Greenhouse Gas Emissions and Removals for Buildings in Hong Kong developed by Environmental Protection Department and Electrical and Mechanical Services Department (HKEPD and HKEMSD, 2010). Next, an automatic measurement tool based on the proposed formulations is developed to evaluate the carbon emissions of a 48-story tall building, One Taikoo Place, in Hong Kong. The carbon emission hotspots in the One Taikoo Place development project are identified, and the recommendations on carbon reduction are given based on the results of the study for future development projects.

2. METHODOLOGY

2.1. Presenting Case Study

The building chosen for the study is One Taikoo Place located at 979 King's Road, Hong Kong. Completed in 2018, One Taikoo Place is the first of two new triple Grade-A office towers in Swire Properties' HK$15 billion Taikoo Place redevelopment project. One Taikoo Place was designed with the highest green building and wellness standards in mind. It is the first commercial building in Asia to achieve WELL Core & Shell Final Platinum, and it is also the first commercial building in Hong Kong to obtain a triple Platinum rating (WELL, BEAM Plus and LEED Final Platinum certification).

The gross floor area of One Taikoo Place is 1 million square feet. This 48-storey office tower was constructed mainly from reinforced concrete using a core-frame structure. Structural steel outriggers are also constructed near mid-level to connect the exterior frame with the central core to improve the lateral stability of the building. Table 1 summarizes the amounts of building materials and energy sources for the construction of One Taikoo Place.

Table 1: Consumption of materials for One Taikoo Place

Materials or Energy	Consumption	Unit
Concrete (Grade 20/20D 75mm)	277,920	kg
Concrete (Grade 30/20D 125mm)	906,960	kg
Concrete (Grade 35/20D 125mm)	2,905,920	kg
Concrete (Grade 45/10D 125mm)	693,600	kg
Concrete (Grade 45/20D 125mm)	28,800	kg
Concrete (Grade 45/20D 125mm WP with Caltite)	78,928,080	kg
Concrete (Grade 45/20D 200mm)	34,119,600	kg
Concrete (Grade 60/20D 200mm)	25,787,760	kg
Concrete (Grade 60/20D 200mm WP with Caltite)	30,837,120	kg
Concrete (Grade 80/20D 200mm)	7,893,840	kg
Reinforcement bar	27,398,220	kg
Structural steel	1,224,717	kg
Timber formwork	1,355	m^3
Glass - Curtain wall, from Spain	97,483	kg
Glass - Curtain wall, from Shanghai	97,483	kg
Glass wall	103,080	kg
Electricity	467,560	kWh
Diesel	17,359	litre

The assessment of carbon emissions for this study is based on a cradle-to-site life cycle, which requires the assessment of emissions from producing the materials used in construction, the emissions arising from material transportation, as well as various on-site construction, waste disposal and treatment activities. The carbon emissions are expressed in terms of a functional unit, i.e. kilogram of carbon dioxide equivalent per construction floor area of the building (i.e. kg CO_2-e/m^2). The carbon emissions include three major types of greenhouse gases, namely carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O)[2]. Different carbon emissions are then converted into CO_2 equivalent using their respective global warming potentials. The proposed formulations cover both direct and indirect sources of carbon emissions. Equations for calculating each source of carbon emissions are illustrated in the following subsections.

2.2. Formulations for Carbon Measurement

2.2.1 Total Carbon Emissions of the Project

The total carbon emissions due to embodied carbon of building materials and carbon emissions from construction activities can be calculated as follows:

$$E_T = [E_1 + E_2 + E_3 + E_4] \cdot A^{-1} \tag{2.1}$$

wherein E_T stands for the total carbon emissions per construction floor area of a tall building (kg CO_2-e/m^2) throughout the cradle-to-site life cycle, E_1 represents the material embodied carbon, E_2 refers to the carbon emissions due to various construction activities, E_3 refers to the carbon emissions due to waste disposal, E_4 is the carbon emissions due to the processing of fresh water and sewage, *A* represents the construction floor area of the building (m^2).

2.2.2 Embodied Carbon of Building Materials

Embodied carbon of building materials includes the emissions due to energy consumption for resource extraction and material manufacture as well as the carbon emissions from transportation for building materials. Below is the formula for calculating the embodied carbon of building materials with references to Gan et al. (2017a):

$$E_1 = \sum_{i=1}^{I} V_i CE_i + \sum_{i=1}^{I} \sum_{j=1}^{J} Q_i D_{i,j} CE_j \tag{2.2}$$

where V_i represents the quantity of building material i (m^3), CE_i stands for the carbon emission factor (kg CO_2-e/m^3). Q_i refers to the weight of building material i (kg), $D_{i,j}$ is the distance of transportation for material *I* (km), CE_j refers to the carbon emission factor for transport means j (kg CO_2-e/tonne·km). Table 2 summarizes the material embodied carbon emission factors used in the case study (One Taikoo Place). The emission factors for different transportation means are taken from WRI and WBCSB (2011), including truck and trailer at 0.204 kg CO_2-e/tonne·km, railway at 0.017 kg CO_2-e/tonne·km, and marine shipment at 0.048 kgCO_2-e/tonne·km.

2.2.3 Carbon Emissions from On-site Fuel and Electricity Consumption

The carbon emissions from fuel combustion and electricity consumption for on-site construction equipment can be calculated as:

$$E_2 = \sum_{e=1}^{E} \sum_{c=1}^{C} E_{ec} CE_e \tag{2.3}$$

in which E_{ec} is the consumption of fuel or electricity e by construction equipment c, CE_e is the carbon emission factor of fuel or electricity e. Table 3 shows the carbon emission factors for different fuel and electricity sources with references to local standards or publications.

2.2.4 Carbon Emissions due to Waste Disposal, Fresh Water Consumption and Sewage Treatment

The emissions from waste disposal did not include emissions generated from waste decomposition at landfill.

[2] The other types of greenhouse gases, hydrofluorocarbons (HFCs), nitrogen triflouride (NF_3), sulphur hexafluoride (SF_6), and perfluorocarbons (PFCs), are not included in the measurement because their contributions to the cradle-to-site carbon emissions of this building are negligible.

Since local contractors utilize mainly diesel-based heavy-duty vehicles to dispose the construction wastes, the carbon emissions can be calculated as:

$$E_3 = \sum_{l=1}^{L} R_l \cdot CE_d \tag{2.4}$$

wherein R_l refers to the product of transportation distance for waste l (km) and the energy consumption indicator of vehicle for waste disposal (litre/km), CE_d is the carbon emission factor of diesel obtained from HKEPD and HKEMSD (2010), which is usually 2.64 kg CO_2-e/litre. The carbon emissions due to electricity used for fresh water consumption and sewage treatment are calculated with reference to HKEPD and HKEMSD, 2010:

$$E_4 = W \times (f_1 + \varepsilon f_2) \tag{2.5}$$

where W is the amount of fresh water consumed on the construction site (m^3), f_1 and f_2 are the electricity emission factors for the processing of fresh water and sewage (kg CO_2-e/m^3), and ε is the percentage of fresh water that enters the sewage system. In this study, all wastewater is assumed to be treated onsite and discharged to storm drain, and thus no discharge into the sewage system.

Table 2: Embodied carbon emission factor for different building materials used in One Taikoo Place

Materials	**Emission factor**	**Unit**	**Description**
Rebar (BF-BOF) – 100% Recycled[a]	0.84	kgCO_2-e/kg	Localized to Hong Kong context according to the literature
Rebar (BF-BOF) – 13% Recycled[b]	2.07	kgCO_2-e/kg	
Structural steel (BF-BOF) – 10% Recycled[c]	2.16	kgCO_2-e/kg	
Concrete (G20/20D)	262	kgCO_2-e/m^3	First-hand data (HKUST)
Concrete (G30/20D 125mm)	222	kgCO_2-e/m^3	Carbon emission factors provided by the main contractor
Concrete (G35/20D 125mm)	230	kgCO_2-e/m^3	
Concrete (G45/10D 125mm)	280	kgCO_2-e/m^3	
Concrete (G45/20D 125mm WP with Caltite)	272	kgCO_2-e/m^3	
Concrete (G45/20D 125mm)	257	kgCO_2-e/m^3	
Concrete (G45/20D 200mm)	295	kgCO_2-e/m^3	
Concrete (G60/20D 200mm)	295	kgCO_2-e/m^3	
Concrete (G60/20D 200mm WP with Caltite)	326	kgCO_2-e/m^3	
Concrete (G80/20D 200mm)	271	kgCO_2-e/m^3	
Glass	1.20	kgCO_2-e/kg	First-hand data (HKUST)
Timber-Plywood for Formwork	1.97	kgCO_2-e/kg	ICE Database (Hammond et al., 2011)

a. Carbon emissions of steel vary greatly due to the manufacturing processes such as Blast Furnace and Basic Oxygen Furnace (BF-BOF) or Electric Arc Furnace (EAF) as well as the content of recycled steel scrap. Below is a list of the carbon emission factors of rebar and structural steel collected from Gan et al. (2017a):

- Pig iron (BF-BOF) – 100% Virgin (2.09 kgCO_2-e/kg), Direct-reduced iron (EAF) – 100% Virgin (1.54 kgCO_2-e/kg), Direct-reduced iron (EAF) – 100% Recycled (0.39 kgCO_2-e/kg)
- Finished steel material – Rebar (0.16 kgCO_2-e/kg), Finished steel material – Structural steel (0.21 kgCO_2-e/kg)

The emission factors for the EAF process rebar are calculated based on the percentage of recycled scrap used. For example, the emission factor for the EAF process rebar with 21% recycled content can be calculated as: 1.54 x (1-21%) + 0.39 x 21% +0.16 = 1.459 kg CO_2-e/kg.

According to World Steel Association (WSA, 2011), the emission factor for BF-BOF rebar (13% scrap) is equal to: 2.09–13% × 1.41 + 0.16 = 2.07 kg CO_2-e/kg; the emission factor for BF-BOF structural steel (10% scrap) is equal to: 2.09–10% × 1.41 + 0.21 = 2.16 kg CO_2-e/kg.

b. The study applied U.S. Green Building Council's definition of the overall recycled content: The overall recycled content = (1/2 pre-consumer recycled content + post-consumer recycled content), which means the same amount of pre-consumer recycled content provide haft environmental benefit compared with post-consumer recycled content.

c. The emission factor for structural steel (BF-BOF) follows a similar calculation procedure as Notes a and b.

Table 3: Emission factor for different energy sources

Energy source	Emission factor	Unit	References
Electricity-CLP	0.54	$kgCO_2$-e/kwh	CLP,2017
Electricity-HKE	0.79	$kgCO_2$-e/kwh	HKE,2017
Towngas	2.82	kg/unit	HKEPD & HKEMSD, 2010
Diesel	2.617	$kgCO_2$-e/l	HKEPD & HKEMSD, 2010
LPG	1.679	$kgCO_2$-e/l	HKEPD & HKEMSD, 2010
Kerosene	2.432	$kgCO_2$-e/l	HKEPD & HKEMSD, 2010
Petrol Oil	2.707	$kgCO_2$-e/l	HKEPD & HKEMSD, 2010
Biodiesel (B5)	2.6	$kgCO_2$-e/l	Acquaye et al., 2012

2.3. Automated Measurement Tools

2.3.1 Data Collection Template

Based on the formulations, site-specific data are collected for individual processes and materials used for One Taikoo Place (see Figure 1). The calculation considers the embodied carbon of major building materials (including concrete, rebar, structural steel, glass and timber formwork) as well as various construction activities. Hence, the data collection template is designed to cover all the major building materials and construction activities afore mentioned. Because difficulties may arise where data is not easily available, some assumptions are made for inputs where the collection of site-specific data is not practicable to allow the calculation. For example, the extraction and manufacture location of timber formwork is assumed within Hong Kong with a transportation distance to project site of 20 km. In addition, the density for timber formwork is 570 kg/m^3 with a maximum three times of reuse on average.

Monthly usage of construction materials			2016						
Construction Material	Unit	Total	Apr	May	Jun	Jul	Aug	Sep	Oct
Concrete (Grade 20/20D 75mm)	kg	277,920	-	-	-	-	-	-	-
Concrete (Grade 30/20D 125mm)	kg	906,960	-	-	-	-	-	-	-
Concrete (Grade 35/20D 125mm)	kg	2,905,920	2,728,080	-	-	-	-	-	-
Concrete (Grade 45/10D 125mm)	kg	693,600	-	-	-	-	-	8,400.00	-
Concrete (Grade 45/20D 125mm)	kg	28,800	-	-	-	-	-	-	-
Concrete (Grade 45/20D 125mm WP with Caltite)	kg	78,928,080	-	3,600	79,680	630,480	463,680	610,080	1,176,720
Concrete (Grade 45/20D 200mm)	kg	34,119,600	-	8,445,600	18,384,240	1,995,600	2,730,000	304,800	271,200
Concrete (Grade 60/20D 200mm)	kg	25,787,760	-	-	-	-	-	-	-
Concrete (Grade 60/20D 200mm WP with Caltite)	kg	30,837,120	-	15,600	314,880	2,877,600	2,093,760	1,881,600	-
Concrete (Grade 80/20D 200mm)	kg	7,893,840	-	-	-	1,414,320	1,267,440	1,354,800	67,200
Reinforcement bar	kg	27,398,220	964,337	2,504,480	1,539,536	945,470	670,980	1,510,190	870,490
Structural steel	kg	1,224,717							
Timber	m3	1,355			190	261	160	134	95
Glass - Curtain Wall, from Spain	kg	97,483							
Glass - Curtain Wall, from Shang Hai	kg	97,483							
Glass Wall	kg	103,080							

Monthly consumption of energy sources for on-site construction equipment				2016						
Energy Source		Unit	Total	Apr	May	Jun	Jul	Aug	Sep	Oct
Diesel oil		L	-							
Biodiesel (B5)		L	39,680	1,426	2,112	3,836	5,030	526	393	266
Gasoline		L	-							
LPG		L	-							
Acetylene		L	-							
Unleaded petrol oil		L	-							
Electricity		kWh	3,153,160	14,210	36,972	43,757	43,368	54,733	50,143	49,946
Other energy source, please specify		Select	-							
Transportation of equipment to site	Select	Select	-							
On-site portable electricity generator	Select	Select	-							

Monthly generation of construction wastes on site			2016						
Type of Construction Waste (e.g., Inert & Non-Inert)	Unit	Total	Apr	May	Jun	Jul	Aug	Sep	Oct
Inert	T	2,122	0	5.55	22.97	41.21	45.25	171	204.56
Non-inert	T	1,558	1.11	24.39	26.35	41.52	38.21	35.06	25.68
Sorting Facility	T	2,855	0	34.33	242.15	286.53	134.36	38.22	37.15
Scraped Steel Metals	T	6,122	0	64.44	392.65	654.34	719.03	199.77	73.59

Fig. 1: Data collection template for inputting the consumption of building materials and energy sources.

2.3.2 Automatic Measurement

Based on the site-specific data collected, carbon emissions are evaluated automatically. Figure 2 shows the automatic measurement tool for calculating the carbon emissions from various building materials and construction activities. The automatic measurement tool, based on a spreadsheet format, reads the consumptions of building materials and energy sources in the data collection template. Next, it estimates automatically the amount of carbon emissions in accordance with the material quantities and corresponding carbon emission factors. The calculated carbon emissions are summarized in terms of three scopes, which are (1) direct greenhouse gases emissions, (2) energy indirect greenhouse gases emissions, and (3) other indirect greenhouse gases emissions. The results show the carbon emission sources towards identifying relevant mitigation measures to control and reduce the carbon emissions.

3.1 Embodied carbon of major construction materials									
17		Major construction materials*		Unit	Total consumption	Unit weight (kg/m3)	Emission factors	Unit of emission factors	Sub-total (kg CO2-e)
17	a	Concrete (Grade 20/20D 75mm)		kg	277,920	2,300	262	kg CO2-e/m3	31,658.71
17	b	Concrete (Grade 30/20D 125mm)		kg	906,960	2,300	0.222	tCO2-e/m3	87,541.36
17	c	Concrete (Grade 35/20D 125mm)		kg	2,905,920	2,300	0.230	tCO2-e/m3	290,592.00
17	d	Concrete (Grade 45/10D 125mm)		kg	693,600	2,300	0.280	tCO2-e/m3	84,438.26
17	e	Concrete (Grade 45/20D 125mm)		kg	28,800	2,300	0.257	tCO2-e/m3	3,218.09
17	f	Concrete (Grade 45/20D 125mm WP with Caltite)		kg	78,928,080	2,300	0.272	tCO2-e/m3	9,334,103.37
17	g	Concrete (Grade 45/20D 200mm)		kg	34,119,600	2,300	0.295	tCO2-e/m3	4,376,209.57
17	h	Concrete (Grade 60/20D 200mm)		kg	25,787,760	2,300	0.295	tCO2-e/m3	3,307,560.52
17	i	Concrete (Grade 60/20D 200mm WP with Caltite)		kg	30,837,120	2,300	0.326	tCO2-e/m3	4,370,826.57
17	j	Concrete (Grade 80/20D 200mm)		kg	7,893,840	2,300	0.271	tCO2-e/m3	930,100.28
17	k1	Reinforcement bar	main supplier 1 (39%	kg	10,575,713	0	0.840	kg CO2-e/kg	8,883,598.85
17	k2	Reinforcement bar	main supplier 2 (16%	kg	4,356,317	0	2.070	kg CO2-e/kg	9,017,576.15
17	k3	Reinforcement bar	others	kg	12,466,190	0	1.525	kg CO2-e/kg	19,010,939.90
17	l	Structural steel		kg	1,224,717	0	2.159	kg CO2-e/kg	2,644,164.00
17	m	Timber	Time of Reuse: 3	m3	1,355	570	1.969	kg CO2-e/kg	507,013.55
17	n	Glass - Curtain Wall, from Spain		kg	97,483	0	1.200	kg CO2-e/kg	116,979.60
17	o	Glass - Curtain Wall, from Shang Hai		kg	97,483	0	1.200	kg CO2-e/kg	116,979.60
17	p	Glass Wall		kg	103,080	0	1.200	kg CO2-e/kg	123,696.00

	Total carbon emissions (kg CO2-e)	Percentage contribution (%)	Carbon emission per floor area (kg CO2-e/m2)
Scope 1 – Direct Emissions	103,168	0.1%	1.11
Scope 2 – Energy Indirect Emissions	2,490,996	3.6%	26.81
Scope 3 – Other Indirect Emissions	67,354,114	96.3%	724.99
3.1 Embodied carbon of major construction materials	63,237,196	90.4%	680.68
3.2 Carbon emissions from transportation of major construction mate	3,993,942	5.7%	42.99
3.3 Carbon emissions due to waste disposal, fresh water consumptio	122,975	0.2%	1.32
Total Project Emission (tonnes CO2-e)	69,948,279	100%	752.92

Fig. 2: Automatic measurement tool in spreadsheet format for calculating carbon emissions of One Taikoo Plac

3. RESULTS AND DISCUSSION

3.1. Carbon Emissions per Construction Floor Area

The proposed formulations and automated measurement tools are examined in evaluating the carbon emissions of One Taikoo Place in Hong Kong. Table 4 shows the carbon measurement results for each emission scope. The results indicated that Other Indirect Emissions significantly outweighs the Direct Emissions (from energy combustion on-site) and Indirect Emissions (from electricity consumption). Of the Other Indirect Emissions, embodied carbon of major building materials accounts for the majority (90.4%) of the total emissions. The percentage contribution of each building material is calculated and summarized in Figure 3.

Table 4: Cradle-to-site carbon measurement results

Scope of carbon measurement	Carbon emissions (kg CO_2-e)	Percentage contribution (%)	Carbon emission per floor area (kg CO_2-e/m^2)
Scope (1) – Direct emissions	103,168	0.1%	0.8
Scope (2) – Energy indirect emissions	2,490,996	3.6%	20.5
Scope (3) – Other indirect emissions	67,354,114	96.3%	553.8
3.1 Embodied carbon of major building materials	63,237,196	90.4%	519.9
Concrete	22,816,249	32.6%	187.6
Rebar	36,912,115	52.8%	303.5
Structural steel	2,644,164	3.8%	21.7
Glass and timber	864,669	1.2%	7.1
3.2 Carbon emissions from transportation of major building materials	3,993,942	5.7%	32.8

Concrete	537,197	0.8%	4.4
Rebar	3,116,832	4.5%	25.6
Structural steel	166,836	0.2%	1.4
Glass and timber	173,077	0.2%	1.4
3.3 Carbon emissions due to waste disposal, sewage water treatment	122,975	0.2%	1.0
Total carbon emissions	69,948,279	100.0%	575.1

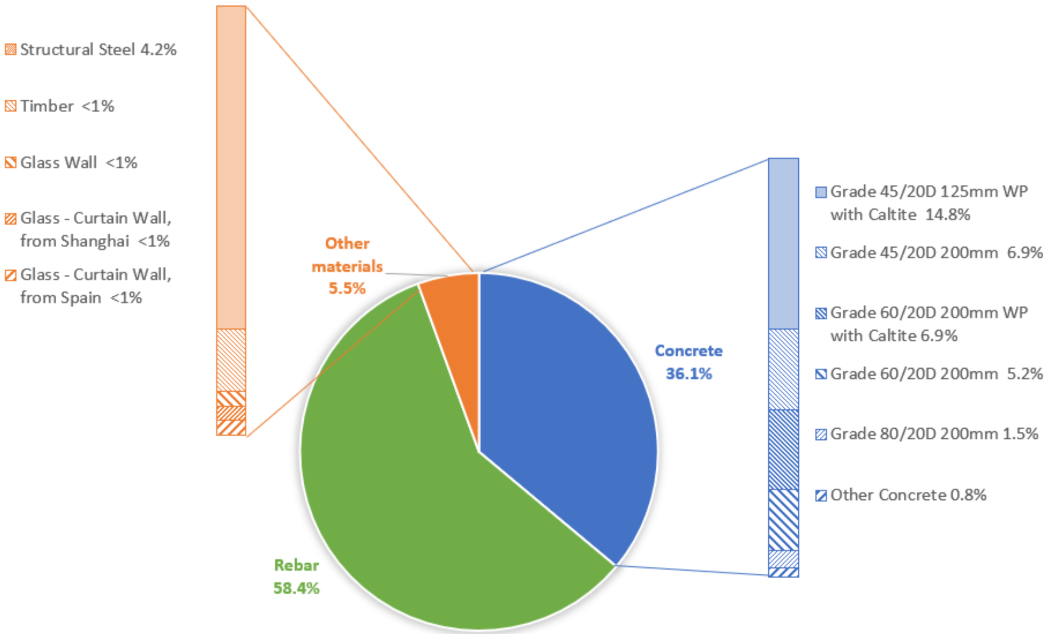

Fig. 3: Breakdown of cradle-to-gate embodied carbon for individual building material

It is demonstrated that rebar and concrete contribute over 94% of the total cradle-to-gate embodied carbon of building materials. Specifically, rebar accounts for about 58% of the total cradle-to-gate embodied carbon, whereas concrete contributes 36% in which Grade 45, Grade 60, and Grade 80 concrete represent approximately 35%. On the other hand, the quantity of glass used in the project is much smaller than concrete, and therefore glass contributes less than 1% of total embodied carbon even though it has a much higher emission factor than concrete. Moreover, the carbon emissions due to the transportation of glass is also negligible (i.e. 0.17% of project's total carbon emissions) although the glass curtain wall are manufactured in Spain and Shanghai, which are far away from the construction site. As such, the carbon reduction strategy should emphasize the embodied carbon of construction materials, particularly from rebar and concrete.

3.2. Recommendations for Sustainable Structural Design

3.2.1 Design of Structural Systems

One Taikoo Place is a 48-storey building constructed mainly from reinforced concrete, using a core-frame structure. Structural steel outriggers are also utilized near mid-level to connect the external frame with the central core. Despite there is no benchmark of embodied carbon for such a 48-storey building using core-frame structure with steel outriggers from the literature, previous relevant study (Gan et al., 2017b) has indicated that the cradle-to-site embodied carbon per gross floor area for a 40-storey core-frame structure using the composite construction method (i.e. mixed use of structural steel and reinforced concrete) is 557 kg CO_2-e/m^2. If the 40-storey core-frame structure changes to the application of 100% structural steel, embodied carbon per floor area increases by around 36% to 759 kg CO_2-e/m^2. On the other hand, using 100% reinforced concrete reduces the embodied carbon of a core-frame structure by 4% to 537 CO_2-e/m^2. There are outriggers utilized in One Taikoo Place to enhance the lateral stability. The carbon emissions of these highly carbon intensive structural steel contribute 3.8% out of total embodied carbon and consequently increase the embodied carbon for One Taikoo Place. Another reason is that One Taikoo Place is a 48-storey building, which is 8-storey taller than the building considered in the literature, and therefore it may be exposed to a stronger wind profile. As a result, larger member size and more structural materials may be needed to reduce the lateral drift caused by wind force. It is recommended to study the embodied carbon for building using core-frame structure with steel outriggers to make a comparison with other typical structural forms (core-frame structure, core-outrigger, and mega-brace structures) for high-rise buildings and provide a benchmark for further comparison in future.

3.2.2 Design of Structural Materials

The embodied carbon of concrete, rebar and structural steel contributes to over 89% of total carbon emissions in One Taikoo Place. Utilizing recycled materials can greatly affect the total embodied carbon of One Taikoo Place. The section below presents the maximum possible carbon reduction by utilizing recycled concrete or steel.

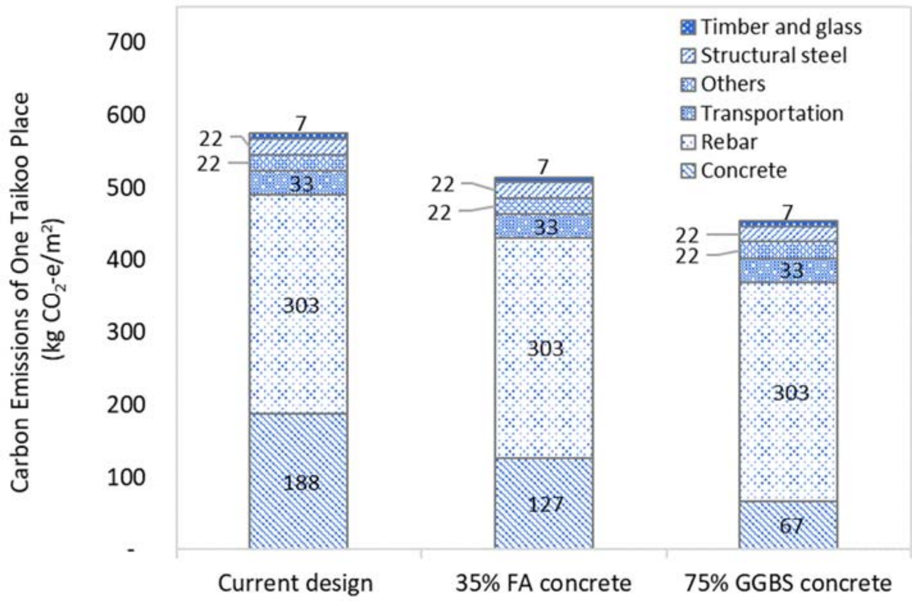

Fig. 4: Carbon emissions of One Taikoo Place with different types of concrete materials: 35% FA concrete and 75% GGBS concrete.

The carbon emissions of concrete are affected by the addition of cement substitutes, e.g. fly ash (FA) and ground granulated blast slag (GGBS). According to the Hong Kong Code of Practice (HKBD, 2013), the maximum rates for cement substitution are 35% FA and 75% GGBS, respectively. Figure 4 shows that utilizing 35% FA concrete can help reduce the embodied carbon of One Taikoo Place from 574 to 514 kg CO_2-e/m^2 (equivalent to 11% reduction), while the use of 75% GGBS concrete can minimize the carbon emissions to 454 kg CO_2-e/m^2 (i.e. 21% reduction). However, when the GGBS in the concrete increased from 0% to 70%, the setting time will be extended from 100 mins to 200 mins (Suresh and Nagaraju, 2015). Hence, the contractor shall consider if the construction schedule is allowable for longer setting time when use high portion of cement substitutes (e.g. 75% GGBS). In addition, FA is a by-product of coal combustion (Li, 2011), which can be obtained from local coal-based power plants. GGBS, however, is a BOF or EF by-product from the iron & steel manufacturing industry (Li, 2011). Since there are no steel factories in Hong Kong, material availability and procurement status should be taken into account when formulating the carbon reduction measures.

In this study, around 88% of the steel rebar are manufactured via BF-BOF production method. The first largest supplier provided 39% of the rebar, which is BF-BOF steel with 100% recycled scrap. The second largest supplier provided 16% of the rebar used in the building, which is BF-BOF steel containing 13% recycled scrap. The rest of rebar suppliers (around 45%) provided either BF-BOF or EAF steel with recycled scrap ranging from 5.5% to 100%.

To facilitate the calculation and analysis, BF-BOF steel containing recycled scrap less than 30% is increased to the maximum allowable content of 30% (WSA, 2014). The emission factors of steel rebar decrease by 4% to 9%. Figure 5 reveals that the use of BF-BOF steel with 30% scrap can help reduce embodied carbon in the One Taikoo

Place by 4% from 575 to 549 kg CO_2-e/m^2. In addition to BF-BOF, EAF is an alternative steel production technology, which can make use of up to 100% recycled scarp. If One Taikoo Place project can use 100% recycled EAF steel, the emission factor of steel rebar can be decreased by 64%, and the most significant reduction in building embodied carbon can be achieved (380 kg CO_2-e/m^2), which is 34% less than that of the current design.

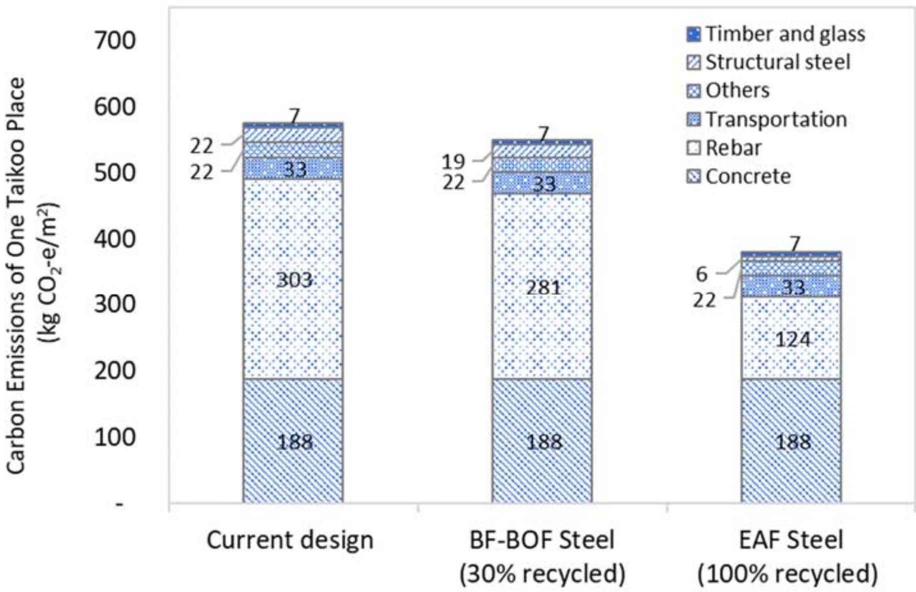

Fig. 5: Carbon emissions of One Taikoo Place with different types of steel materials: BF-BOF steel (30% recycled) and EAF steel (100% recycled)

3.2.3 Improvement Opportunities for Future Projects

At the beginning of the study, first-hand data are expected to be collected from material manufacturers for the calculation of carbon emission factors of the major building materials. The emission factors for concrete are obtained from the main contractor, who operates its own concrete batching plants and have obtained carbon labels for its concrete products. However, first-hand data are still needed from the suppliers of other materials such as rebar, structural steel, timber formwork, and glass. The data to be collected should cover the raw materials, energy consumption for material manufacture, amount of recycled content, fuel mix, and type of the production technologies, which in reality are very difficult to obtain due to the confidentiality issue, lack of operational control, etc. As such, it is recommended to plan the data collection and to specify the data request (e.g. in the contract) so that material manufacturers or suppliers can provide corresponding data for carbon auditing exercises.

In addition, the embodied carbon of a building is sensitive to certain building design parameters (such as material specifications and structural form design). More attentions should be paid to the collection of design parameters that significantly impact the building embodied carbon. For instance, the carbon emission factor of concrete varies considerably with increasing concrete strength. These material specifications, including the strength, production technology, and recycled content, should be clearly described during the data collection. In addition to material specifications, different types of structural forms also affect the structural efficiency and the amount of materials required. It is suggested to collect details of significant design parameters to facilitate the analysis of the carbon emission hotspots and to provide more insights on the embodied carbon reduction measures. It also helps decision makers to develop corresponding low carbon strategy for climate mitigation.

Last but the least, the embodied carbon associated with the production of rebar, structural steel and concrete contributes to 89.2% of total carbon emissions in One Taikoo Place. This is followed by the carbon emission from transportation of rebar, structural steel and concrete to the project site (5.5%) and carbon emissions from on-site electricity consumption (3.6%). The embodied carbon and carbon emissions from transportation of timber and glass account for only 0.73% and 0.75% of the total embodied carbon, respectively. Based on the rule of thumb in the specification for the assessment of life cycle greenhouse gas emissions of goods and services, a threshold of

1% is commonly used to exclude those minor carbon emission sources over the product life cycle. However, it should also be noted that the total exclusions should not exceed 5% of the overall product carbon emissions. It is suggested that when carrying out similar carbon accounting exercises, the scope can be properly defined to exclude the subtle carbon emission sources (such as timber formwork and glass) in order to save the workload and effort for data collection. Moreover, the carbon emissions due to the production and transportation of glass account for less than 1% of project's total carbon emissions. Therefore, glass can be also excluded from the scope of study. More attentions can be put on the data collection, evaluation, and analysis of the major carbon emission sources such as the embodied carbon of concrete and steel rebar.

4. CONCLUSIONS

This paper presents the measurement of carbon emissions from construction activities and building materials to underpin the sustainable structural design of tall commercial buildings. Formulations for carbon measurement are proposed, taking into consideration of the cradle-to-site emissions associated with resource extraction, material manufacturing, transportation, on-site construction and waste disposal and treatment, with application of locally or regionally specific emission factors. An automatic carbon measurement tool is developed to quantify the amount of carbon emissions from One Taikoo Place, Hong Kong. The results provide deeper understandings into the environmental performance of tall commercial buildings for different structural designs. However, several limitations still exist which call for improvements for future development projects. First, it is recommended to plan the data collection and to specify the data request so that material manufacturers or suppliers can provide associated data at the beginning of the study for carbon auditing. In addition, it is suggested to collect details of significant design parameters at the beginning of the carbon measurement so as to facilitate the analysis and to provide more insights on the embodied carbon reduction measures. Last but not least, more attentions should be spent on the data collection, evaluation, and analysis of the major carbon emission sources such as the embodied carbon of concrete and steel rebar. While the carbon measurement in this study was conducted locally using region-specific emission factors, there's possibility to generalise the formulation and emission factors for evaluating the sustainability performance of high-rise buildings.

5. Acknowledgement

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Optimization algorithms for construction site layout planning: A review

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ABSTRACT: *Well-planned site layouts are required for on-site construction activities that usually cause various conflicts. Construction site layout planning (CSLP) is conducted to assign optimal positions to temporary facilities in order to reduce costs and improve construction productivity and safety levels. Considered an NP-hard problem, an optimal layout in CSLP problems cannot be generated in polynomial time. Optimization algorithms play a central role in addressing complexity since they are not problem-specific. Identifying their pros, cons, and potential alternatives can benefit the scholars and practitioners significantly. However, there is a lack of systematic reviews of optimization algorithms for CSLP for the purpose of comparison and selection of algorithms. Therefore, this study reviews the research produced in the last decade on CSLP and optimization algorithms with the intent of addressing the research gap in knowledge for future research. Seventy-five studies related to optimization algorithms for CSLP are identified and reviewed with a systematic protocol consisting of identification, screening, eligibility, and review. The findings are synthesized to present an overview; the pros, cons and alternatives of optimization algorithms; and other techniques for CSLP. Future research directions are also outlined, focusing on requirements for the consideration of optimization objectives and layout objects, and ways to improve hybrid optimization algorithms for CSLP. Through a systematic literature review, this study offers a holistic insight into optimization algorithms for CSLP, including the trends of publications, prevalent algorithms, the pros and cons of these algorithms, as well as other optimization techniques for the improvement of CSLP. The findings are also recommended both for the theoretical research and practical applications.*

KEYWORDS: *Construction site layout planning, optimization algorithms, systematic literature review*

1. INTRODUCTION

The traditional construction management involves various manual decision-making problems and needs a paradigm shift to a smart approach (Niu et al., 2016, Wang et al., 2019). Smart techniques can provide accurate and reliable information for making informed decisions in construction management, especially on-site management (Kim et al., 2013). Construction site layout planning (CSLP) is a vital decision-making process for on-site construction management as the deficiencies of human-centric decisions can result in cost overruns, safety issues, and schedule delays (Liao et al., 2011).

CSLP is usually conducted as an optimization problem to determine the optimal layouts of temporary facilities, such as residential areas, site offices, material storage, and processing areas; the appropriate space allocations for construction equipment; and efficient plans for on-site paths (Sadeghpour and Andayesh, 2015) considering the constraints of the site. Because of rapid urbanization, the space for construction sites is increasingly restricted (Kumar and Cheng, 2015). A well-planned site layout has significant impacts on construction productivity in large-scale projects as well. Moreover, on-site conflicts often occur due to the increasing complexity of interaction between different activities (Song et al., 2016). These constraints also magnify the complexity of CSLP optimization (Cheng and Chang, 2019). Therefore, appropriate and efficient optimization techniques are required to address this problem.

Optimization algorithms can be viewed as search techniques for finding optimal or satisfactory solutions to an optimization problem with various constraints. Deterministic algorithms, such as linear programming (LP) and approximate dynamic programming (ADP), and stochastic algorithms, such as genetic algorithm (GA), ant colony optimization (ACO), and particle swarm optimization (PSO) are exploited in existing studies (Liao et al., 2011, Briskorn and Dienstknecht, 2018).

Since optimization algorithms contribute to addressing the CSLP problem and provide acceptable smart solutions, it is necessary to have an understanding of the status quo of optimization algorithms for CSLP, including:

- What is the overview of publications on optimization algorithms for CSLP?

- What are the prevalent optimization algorithms for CSLP? And how to categorize these optimization algorithms?
- What are the pros and cons of these optimization algorithms?
- What are the research gaps and future directions of optimization algorithms for CSLP?

This study aims to answer the above research questions by conducting a systematic review of optimization algorithms for CSLP with an analysis of publishing framework, the pros, and cons of existing studies, and a proposal of future directions. Altogether 75 studies from 29 related journals published in English over the last decade were identified and reviewed. The remainder of this study is organized as follows; Section 2 explains the research approach to the systematic review, results are discussed in Section 3, Section 4 identifies future research directions, and conclusions are presented in Section 5.

2. RESEARCH APPROACH

According to Booth et al. (2016), the protocol of a systematic review is used to acquire up-to-date and high-quality articles. A protocol consisting of identification, screening, eligibility, and review, is an appropriate methodological approach to find existing studies on CSLP and optimization algorithms to identify gaps in knowledge and future research directions.

Records were identified through three databases, Web of Science (WOS), ScienceDirect, and Scopus. The period of publications ranged from January 2009 to June 2019 and the field "*Title, abstract, keywords*" in databases was used. A detailed search was conducted using the field "*Title, abstract, keywords – layout planning, algorithm, construction*". As a consequence, 200 records were initially identified: 89 from Web of Science, 32 from ScienceDirect, and 79 from Scopus. Furthermore, an additional 42 records were identified under the search criteria "*Title, abstract, keywords – site layout, algorithm, construction*".

After removing duplicates, the total number of records was reduced to 151 — 30 conference papers and 121 journal articles. Conference papers were excluded for reasons of the quality. The full-text articles were assessed for eligibility and 40 were excluded because they were irrelevant, pertaining to topics such as the manufacturing sector (9), scheduling (8), the modular manufacturing sector (4), on-site operations (4), cutting layouts of materials (2), urban layout (2), airport layout (2), and others (9). In addition, review articles (3), articles whose text was unavailable texts (2), and those published in other languages (1) were also excluded because of the predefined research aim. Finally, 75 studies were selected for detailed analysis in this research.

To achieve the research aim, a coding structure is also proposed and the themes of the selected studies are divided into two parts to analyze them, as shown in Table 1. The first part relates to the publishing framework of the studies, including article title, publication year, journal, and country and region; the second part, for comparative analysis of the review topic, contains major types and distinguishing features of optimization algorithms employed for solving CSLP problems.

Table 1. Theme categories of coding structure

Category	Theme	Description
Part 1	(1) Article title	the title of the article
	(2) Publication year	the year the article was published
	(3) Journal	the source of the article
	(4) Country & region	the organizational address of the first author in the article
Part 2	(5) Optimization objective	factors considered in the optimization objective function
	(6) Layout object	facilities, equipment and roads optimized in CSLP
	(7) Algorithm	optimization algorithms for solving CSLP
	(8) Search type	the way used to search and find the optimal solution
	(9) Solution representation	representation of solutions in various algorithms
	(10) Initial solution generation	generation of initial solutions in various algorithms
	(11) Sub-algorithm	algorithms for improving the quality of solutions in CSLP
	(12) Developed tool	self-developed tools based on algorithms for solving CSLP
	(13) Commercial software	environment for various algorithms for solving CSLP

3. RESULTS AND DISCUSSIONS

The results of the analysis are divided into two based on the categorized themes of the coding structure. Section 3.1 presents analysis of themes (1) to (4), representing the publishing framework of the selected studies. Section 3.2 presents a comprehensive analysis of optimization algorithms for CSLP identified from themes (5) to (13), including the overview, pros and cons, and other techniques for improving CSLP solutions.

3.1 Publishing framework analysis

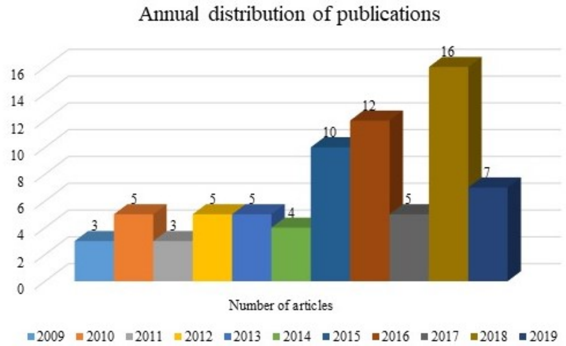

Fig. 1. Annual distribution of publications

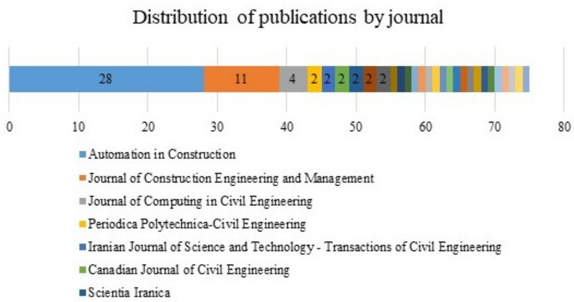

Fig. 2. Distribution of publications by journal

Fig. 1 shows the annual distribution of publications on optimization algorithms applied to CSLP. In general, the number of articles related to the topic has increased in the last decade, especially during the last five years.

The selected studies were published in 29 types of journals included by the aforementioned databases. The distribution of publications by journal is presented in Fig. 2. *Automation in Construction* and *Journal of Construction Engineering and Management* were more appreciated than other journals due to their high impact factors, with 28 and 11 publications, respectively.

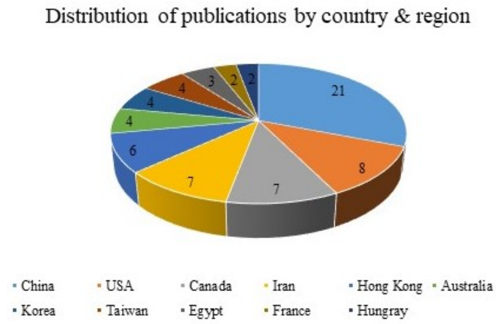

Fig. 3. Amount distribution in search period

Fig. 4. Location distribution in last three years

The distribution of publications by country and region with a minimum of two published articles is depicted in Fig. 3. To ensure understanding and acceptance, the organizational address of the first author of article was exploited to conduct the analysis. China, USA, Canada, and Iran were the top four countries publishing work on the topic in the search period, but in the last three years, articles were published by organizations in 14 countries and regions. Note that developing countries and regions have paid more attention than their developed counterparts in the last three years and half of these are located in Asia (see in Fig. 4).

3.2 Highlights of comparative analysis

As mentioned above, in this section, the results of comparative analysis are listed from themes (5) to (13). The overview of optimization methods (e.g., optimization algorithms and simulation methods) and corresponding pros and cons are presented. For the sake of improving the search efficiency of optimization algorithms, some other techniques adopted in the selected studies are also introduced.

3.2.1 Overview of optimization methods for solving CSLP

Table 2 presents the selected studies. The first column represents the source from which the analytic results are derived. Four major types of optimization methods exploited in the selected studies are presented in the second column; meta-heuristic algorithms (49), heuristic algorithms (2), exact algorithms (15), evaluation methods (4), and simulation methods (5). Because of the complexity of CSLP solutions, a general optimization algorithm (e.g., GA, ACO, and PSO) is not always efficient and effective. Therefore, some other optimization algorithms and variants of the general algorithms are utilized. For the sake of transparency in the analytic results, the general algorithm primarily utilized in the research, other algorithms for enhancing search capability (Hybrid) or evaluating the performance (Comparative), and the variants of optimization algorithms are arranged in the next four columns.

Table 2. Comparative analysis of optimization methods in CSLP

Source	Method Type	General Algorithm	Other Algorithm	Variant	Relationship
(Li et al., 2019)	Meta-heuristic	GA			
(Farmakis and Chassiakos, 2018)					
(Khalafallah and Hyari, 2018)				NSGA-Ⅱ	
(Song et al., 2018b)				Bi-GA	
(El Meouche et al., 2018)					
(Li, 2018)			ACO	Pareto-based ACO-GA	Hybrid
(RazaviAlavi and AbouRizk, 2017b)					
(Song et al., 2017)					
(RazaviAlavi and AbouRizk, 2017a)					
(Abune'meh et al., 2016)					
(Abotaleb et al., 2016)					
(Xu et al., 2016a)			SA	MOSA-based GA	Hybrid
(Xu et al., 2016b)				frs-BLMOGA	
(Akanmu et al., 2016)					
(Kumar and Cheng, 2015)					
(Alanjari et al., 2015)					
(Abdelmegid et al., 2015)					
(Said and El-Rayes, 2013a)					
(Said and El-Rayes, 2011)					
(Said and El-Rayes, 2010)				MOGA	
(Lam et al., 2009)			ACO	MMAS-GA	Hybrid
(Zhou et al., 2009)					
(Benjaoran and Peansupap, 2019)		PSO			
(Oral et al., 2018)			GA, ACO		Comparative
(Song et al., 2018a)				Bi-PSO	
(Song et al., 2016)			GA	HGABPSO	Hybrid
(Li et al., 2015)				MOBLPSO	
(Xu and Song, 2015)				p-based MOPSO	
(Adrian et al., 2015)			GA, PSO		Comparative
(Xu and Li, 2012)				MOPSO	
(Ning et al., 2019)		ACO	GA	GA-ACO	Hybrid
(Ning et al., 2018)					
(Ning and Lam, 2013)				Pareto-based ACO	
(Ning et al., 2011)				MMAS, Pareto-based ACO	
(Ning et al., 2010)				MMAS	
(Kaveh et al., 2018b)		CBO	PSO	ENSCBO	Comparative
(Kaveh and Vazirinia, 2018)			VPS, EVPS, CBO	ECBO	Comparative
(Kaveh et al., 2016)			CBO	ECBO	Comparative
(Lien and Cheng, 2014)		BA[1]	PSO	PBA	Hybrid
(Lien and Cheng, 2012)			PSO	PBA	Hybrid
(Kalmár et al., 2014)		BA[2]	MA, HA, CA	BEA	Hybrid
(Yahya and Saka, 2014)		ABC		MOABC	
(Kaveh et al., 2018a)		CSS		MCSS	
(Wang et al., 2015)		FA			
(Gholizadeh et al., 2010)		HS			
(Park and An, 2012)		SOMO			

(Cheng and Chang, 2019)		SOS			
(Kaveh and Vazirinia, 2019)		VPS	CSS, WOA, VPS	EVPS	Comparative
(Kaveh and Moghaddam, 2018)		WOA	CBO	WOA-CBO	Hybrid
(Pem and Malyusz, 2016)	Heuristic	CPA			
(Andayesh and Sadeghpour, 2013)		MTPE			
(Liu and Lu, 2015)	Exact	LP			
(Al Hawarneh et al., 2019)				BILP	
(Liu et al., 2018b)				BILP	
(Huang and Wong, 2019)				BMILP	
(Hammad et al., 2017)				BMILP	
(Huang and Wong, 2017)				BMILP	
(Huang and Wong, 2015)				BMILP	
(Huang et al., 2011)				BMILP	
(Huang et al., 2010)			GA	BMILP	Comparative
(Hammad et al., 2016b)		IP		MIP	
(Wong et al., 2010)			GA	MIP	Comparative
(Said and El-Rayes, 2013b)		ADP	GA		Comparative
(El-Rayes and Said, 2009)					
(Hammad et al., 2016a)		NLP		MOMINLP	
(Park et al., 2012)		DC			
(Jin et al., 2018)	Evaluation	ANP			
(Ning et al., 2016)		TOPSIS			
(Kang and Seo, 2013)		GIS-based LE			
(Su et al., 2012)		GIS-based MLEM			
(Younes and Marzouk, 2018)	Simulation	ABS			
(Liu et al., 2018a)		VC			
(ElNimr et al., 2016)		DES			
(Pradhananga and Teizer, 2015)		CBS			
(Moon et al., 2014)					

Table 2 makes it clear that the meta-heuristic and exact optimization algorithms are major methods for solving CSLP. GA, PSO, and ACO in the meta-heuristic algorithms, and linear programming (LP) in the exact algorithms, are the general algorithms most appreciated in searching for CSLP solutions.

3.2.2 Pros, cons and potential alternatives of optimization algorithms

Meta-heuristic algorithms are one of the most popular optimization methods for solving CSLP problems in the analytic studies, for four major reasons: (1) a global optimal solution is impossible (Ning et al., 2019, Said and El-Rayes, 2013a) or cannot be found at a reasonable cost (e.g., time) (Benjaoran and Peansupap, 2019, Farmakis and Chassiakos, 2018, Kaveh et al., 2018a, RazaviAlavi and AbouRizk, 2017a, Li et al., 2015, Xu and Song, 2015, Kalmár et al., 2014); (2) the algorithms are not problem-specific (Li et al., 2019, Khalafallah and Hyari, 2018) and the derivatives of objective functions are not required (Kaveh and Vazirinia, 2019, Xu et al., 2016b, Gholizadeh et al., 2010, Zhou et al., 2009); (3) CSLP is a combinational optimization problem with computational complexities (Cheng and Chang, 2019, Kaveh and Moghaddam, 2018, Ning et al., 2018, Song et al., 2018b, Song et al., 2017, Kaveh et al., 2016, Akanmu et al., 2016, Xu and Song, 2015, Yahya and Saka, 2014) and becomes more and more complex in large-scale and congested sites (Kumar and Cheng, 2015, Kaveh et al., 2018b, Abdelmegid et al., 2015, Xu and Li, 2012, Said and El-Rayes, 2011); and (4) developing bi-level models make it difficult to use exact algorithms to find all feasible solutions (Song et al., 2018a, Song et al., 2016, Li et al., 2015). Nevertheless, the randomness in searching the solution space often causes local optimal solutions and a near-optimal solution is always considered the final CSLP solution (Benjaoran and Peansupap, 2019, Huang and Wong, 2017).

Exact algorithms are also widely utilized in solving CSLP problems since they can reduce the randomness when searching the solution space to find a global optimal solution (Al Hawarneh et al., 2019, Huang and Wong, 2019, Huang and Wong, 2017). The standard branch-and-bound method is usually utilized to explore all feasible solutions (Huang and Wong, 2019, Huang and Wong, 2017, Hammad et al., 2016a, Huang and Wong, 2015, Huang et al., 2011, Wong et al., 2010, Huang et al., 2010). However, the computing complexity will be rapidly increased when the number of layout facilities increases.

Heuristic algorithms are often employed when the near-optimal solutions are sufficient and the cost of finding a global solution is expensive (Pem and Malyusz, 2016, Andayesh and Sadeghpour, 2013). Unlike the search process in meta-heuristic algorithms with randomness, the heuristic algorithms try to check all the neighbors of a feasible solution and to improve the quality of solutions. Although heuristic algorithms can search for a solution in a large-scale space, the quality of solutions depends on the location of initial solutions in the space.

The selected optimization algorithms and types of predefined problems have determined the solution representations, such as the types and number of variables, and encoding forms and length, which contribute to the utilization of optimization algorithms. Considering locations and spaces available for layout facilities, the CSLP problem can be divided into discrete, grid-based and continuous problems (Sadeghpour and Andayesh, 2015).Since the number, dimensions, and locations of available locations are predetermined in the discrete problems, binary variables with a value of "0-1" are mostly utilized to represent solutions in various optimization algorithms in the interest of simplicity. The permutation matrix has been exploited in both metaheuristic algorithms (Kaveh and Vazirinia, 2019, Li et al., 2019, Song et al., 2018a, Farmakis and Chassiakos, 2018, Kaveh et al., 2018a, Song et al., 2017, Kaveh et al., 2016, Song et al., 2016, Xu et al., 2016a, Akanmu et al., 2016, Adrian et al., 2015, Gholizadeh et al., 2010) and exact algorithms (Huang and Wong, 2019, Liu et al., 2018b, Hammad et al., 2016a, Huang and Wong, 2015, Wong et al., 2010, Huang et al., 2010). However, this is not convenient for some metaheuristic algorithms (e.g., GA) (Song et al., 2018b, Wang et al., 2015, Li et al., 2015, Ning and Lam, 2013, Lien and Cheng, 2012, Ning et al., 2011, Ning et al., 2010) in which each representation of a solution is often encoded as a string. For this purpose, a string-based representation with a value of "0-1" is proposed as a variant of the permutation matrix. Infeasible solutions may be generated in accordance with the violation of the condition that a facility must be set up in a location at the same time.

Both integer and priority values have been introduced into the string-based representation as well considering the advantages of encoding solutions in metaheuristic algorithms. In the integer-based string, the integer in the string indicates the number of facilities or locations assigned to corresponding locations or facilities. The representation of "facility to location" and "location to facility" is exploited. When the number of facilities equals to that of locations, both of the two representations are effective (Kaveh and Vazirinia, 2018, Hammad et al., 2016b). In contrast, if there are more locations than facilities, the "location to facility" representation will be more appropriate because of the reduction of the length of the encoding in optimization algorithms (Xu et al., 2016b, Xu and Li, 2012, Lam et al., 2009, Kaveh and Moghaddam, 2018). The priority-based representation is presented. This kind of representation provides a set of priority values for the layout facilities and contributes to the application of a continuous form of optimization algorithms instead of a discrete one (Park and An, 2012, Gholizadeh et al., 2010).

3.2.3 Other techniques for enhancement in CSLP

Apart from optimization algorithms for solving CSLP problems, other algorithms, defined as sub-algorithms in this research, are also employed to improve the quality of outputs instead of directly solving the problem. The sub-algorithms are composed of four major aspects, including travel distance calculation, search capability improvement, on-site data processing, and layout conflict detection.

The travel distance between the origin and destination points can be represented by the Euclidean distance in the interest of simplicity. The Dijkstra' algorithm (El Meouche et al., 2018, Kang and Seo, 2013) is utilized to find the least cost path between facilities by calculating the minimum weight sum of link paths. Moreover, considering the existing obstacles on site, modified Euclidean distance calculation algorithms are provided, such as the Site Blocks algorithm (Al Hawarneh et al., 2019) and the Diagonal Direction algorithm (Park et al., 2012), by introducing a transfer point to pass the obstacle and by executing the diagonal movement to approximate the actual distance instead of the Euclidean distance, respectively.

In contrast to the Euclidean distance, the Manhattan distance has the advantages of finding the shortest path with on-site obstacles as a transportation network can be generated. The Short Distance algorithm (Abotaleb et al., 2016) is used to find the shortest path between two points with obstacles by generating a site mesh. On the other hand, to solve problems with multiple origin and multiple destination points, the Floyd-Warshall's algorithm (Hammad et al., 2017, Liu and Lu, 2015) is utilized by adding weights to generate the shortest distance matrix in the Manhattan metric. In addition, the Travel Path Distance algorithm (Benjaoran and Peansupap, 2019) is utilized to calculate the actual distance consisting of a first distance between the entrance of an origin facility and the nearest access road, a second distance along the access road, and a third distance between the access road and the nearest entrance of a destination facility. Nevertheless, the Manhattan distance is calculated longer than the Euclidean distance.

The A* algorithm is proposed, integrating the Euclidean metric and Manhattan metrics. According to (ElNimr et al., 2016), the actual travel distance is provided by the A* algorithm with a search mechanism that calculates the exact distance between the origin and current points and searches for the distance between the current and destination points using a heuristic method. Meanwhile, the A* algorithm can also be utilized to find the shortest path by overcoming the disadvantage of linear distances considering existing obstacles (Kumar and Cheng, 2015).

4. FUTURE RESEARCH DIRECTIONS

Layout costs, potential safety risks, and on-site productivity are the major optimization objectives considered in CSLP. Cost-based objectives are often formulated by transportation distances (Cheng and Chang, 2019, Kaveh et al., 2018a) and weighted distances (Benjaoran and Peansupap, 2019, RazaviAlavi and AbouRizk, 2017b) between facilities. Potential safety risks are always minimized through reducing the frequencies of interaction flows between risky points (Oral et al., 2018, Kaveh et al., 2018b) and by fulfilling the requirements of geographic relationships (e.g., maximizing the safety distance) (Huang and Wong, 2017, Xu and Li, 2012). Minimizing the operation time can be formulated to optimize construction productivity (Wang et al., 2015, Kalmár et al., 2014). As the complexity and congestion of construction sites increases, the CSLP has a considerable impact on the health and safety of on-site workers. However, the occupational health and safety (OHS) of workers is not fully considered. Although some harmful factors, such as construction noise (Ning et al., 2019, Hammad et al., 2016a), dust and hazardous materials (Ning et al., 2018), and toxic gases and radiation (Liu et al., 2018b), are taken into account, this consideration is not systematic. More attention should be paid to the OHS for the enrichment of optimization objectives when employing optimization algorithms.

In the selected studies, the quality of solutions generated by GA improves initial optimizing solutions reached with SA (Xu et al., 2016a) and ACO (Li, 2018, Lam et al., 2009). The search process is also more efficient with hybrid algorithms, such as categorizing whales with the concept of colliding bodies (Kaveh and Moghaddam, 2018), enhancing particles with genetic operators (Song et al., 2016), and improving bacterial convergence rates with heuristics (Kalmár et al., 2014). However, the merits of exact algorithms have not been considered to improve the search capacity of various optimization algorithms. Section 3.2.2 shows that metaheuristic algorithms, heuristic algorithms, and exact algorithms can be employed to solve various optimization problems in terms of their unique search capacity. Due to their random searching in the solution domain, metaheuristic algorithms can find an optimal or satisfactory solution within a large solution domain (Ning et al., 2019, Li et al., 2019). However, a local optimal solution may be obtained instead of a global one (Al Hawarneh et al., 2019). In contrast to metaheuristic algorithms, exact algorithms can find a global optimal solution, while very limited layout objects can be modeled considering the computing costs (Khalafallah and Hyari, 2018, Song et al., 2017, Song et al., 2016). Therefore, the significant value of integrating exact algorithms with metaheuristic algorithms is twofold: (1) it improves global search capacity, and (2) accelerates convergence speed.

5. CONCLUSIONS

This study presents a systematic literature review to illustrate the status quo of research using optimization algorithms to solve CSLP problems. It is based on a database search for studies published in English from January 2009 to June 2019 on construction, layout planning, site layout, and optimization algorithms. The search was limited to three major databases (WOS, ScienceDirect, and Scopus). Seventy-five studies were selected and analyzed following a systematic review protocol, removing duplicates and assessing eligibility. The selected studies have been described according to their publishing framework (Part 1) and comparative analysis (Part 2). This review is of significant value in advancing the selection and application of optimization algorithms for solving CSLP problems.

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The Need for Capacity Building of SMES for Lean Construction Adoption: A Literature Review

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ABSTRACT: *Small and Medium Sized enterprises (SMEs) are one of the most important forces for economic development. SMEs account for approximately 90% of businesses and more than 50% of employment worldwide. Notwithstanding SMEs significant contributions, they face fundamental problems such as low product quality, high cost overruns, and huge material wastages among others. These problems lead to high attrition rate and widespread underperformance. Lean construction is a production delivery system with the potential to deliver exceptional performance improvement for any organization and a possible solution to the many problems of SMEs. However, SMEs lack the needed resources which constraints their lean implementation. Previous works have concentrated on what SMEs can and should do within their limited capacity. However, the use of the isolated tools and practices fail because lean is a system that has to be implemented in a holistic manner. The study addresses the need for capacity building of Construction SMEs to fully implement the lean philosophy. This research is based on a review of pertinent literature.. The data was obtained through databases such Emerald Insight, Taylor and Francis etc,. The findings from the review of literature suggest that SMEs capacity needs to be built in terms of finances, human and technical expertise, organizational culture and managerial resources. SMEs capacity needs to be built in order to successfully adopt lean construction.*

KEYWORDS: *SMEs, Lean Construction, Capacity Building, Process Improvement, Value*

1. INTRODUCTION

Broadly, organisations can simply be categorised into two groups: Large Enterprises (LEs) and Small and Medium Sized enterprises (SMEs) (Hu et al., 2015). The role of SMEs as a means for building a robust economic system has long been acknowledged. SMEs are one of the most important forces for economic development. These firms account for approximately 90% of businesses and more than 50% of employment worldwide, and in developing countries in particular, they account for 45% of formal employment (Bauchet and Morduch, 2013). SMEs therefore have crucial roles to play in stimulating economic growth in developing countries through employment generation, and subsequently poverty alleviation.

Notwithstanding SMEs significant contributions to economic development, they are faced with fundamental problems such as low product quality, low working efficiency, high cost overruns, and huge material wastage among others (Shang, 2013; Kamal and Flanangan, 2014). Construction SMEs and the industry as a whole has been criticized with regards to its adversarial nature, the take up of new technologies and processes and issues associated with organizational management (Miller et al., 2002). Lean construction (LC) is a production delivery system with the potential to deliver exceptional performance improvement in the construction industry (Sage et al., 2012). Lean is a possible solution to the many problems faced by construction SMEs (Bhamu and Sangwan, 2014). Any methodology to make an enterprise lean always reduces waste and maximizes value anywhere in the company. The aim of this study therefore is to provide a state-of-the-art justification for the need to build the capacity of Construction SMEs to fully adopt Lean construction. The research sought to answer the question of whether there is a need for capacity building of SMEs for lean construction adoption.

2. RESEARCH METHODOLOGY

Literature review has been extensively used in Construction Management research as a typical methodology for advancing knowledge in specific topics (Li et al., 2014). A systematic literature search was performed based on a review of empirical and theoretical studies already published. It was utilized because of the rigorous and transparent form of the review. It involved identifying, synthesizing and assessing all available evidences in order to generate robust and empirically derived answers to the research question (Okoli and Schabram, 2010). This study follows the comprehensive stages for the systematic review developed by Tranfield et al. (2003). The process is planning the review; then conducting the review; and finally reporting and disseminating the information reviewed. Past research on Lean construction and SMEs were obtained primarily from research databases including Research Gate, International Group for Lean Construction (IGLC), Science Direct (Elsevier), Emerald Insight, Taylor and Francis, Google Scholar and other internet sources. The initial descriptors used for the search were "Lean construction," "construction SMEs," "Lean and construction SMEs. The initial descriptors were used to search all the databases. A total of 114 articles were initially identified, out of which 63 were found to be valid for the analysis.

3. CONTRIBUTIONS OF CONSTRUCTION SMEs TO ECONOMIC DEVELOPMENT

SMEs are considered as being the bed-rock upon which economies grow. Their relevance and significance can be seen in all aspects of the socio-economic lives of countries such as job creation, poverty reduction, and spreading development to all parts of countries especially in the rural areas (Pressey et al., 2009). Small construction firms in Ghana constitute about 95% of contractors, over 90% of the job market, and nearly 80% of all short-term employment (Amoah et al., 2011). Both developed and developing countries have realized that SMEs have become one of the key instruments to use to face economic and social problems, and to achieve development objectives (Bouazza, 2015; Maksimov et al., 2016). Irrespective of the degree of development and standard of living of a nation, SMEs are the biggest contributors to GDP and employment. SMEs are critical in the structure of any construction industry, as they form majority of the firms (Gyadu-Asiedu, 2009; Amoah et al., 2011). The structure of the construction industry in every country is pyramidal in shape. There are very few large firms at the top, which are able to work in many geographical locations and on a wide range of projects (Amoah et al., 2011). Also, there exist a strong linkage between the construction industry and economic growth of a country (Osei, 2013; Ackah et al., 2014;). Undeniably, the construction industry is a strategic asset for socio-economic development. The industry has the potential of championing the accelerated development that could take millions out of poverty (Ahadzie, 2010) and also help in developing other sectors of the economy (Osei, 2013; Ackah et al., 2014). According to Osei (2013), the industry has a lot of significance in the achievement of national socio-economic development goals of providing infrastructure, employment and reduction of poverty.

4. CHALLENGES TO CONSTRUCTION SMEs DEVELOPMENT

Notwithstanding the significant economic contributions of small construction firms, the challenges these firms face are overwhelming (Amoah et al., 2011). It is generally recognized that SMEs face unique challenges, which affect their growth and profitability (Amoah et al., 2011; Shilinge, 2016). These include: lack of managerial training and experience, inadequate education and skills, lack of credit, national policy and regulatory environment, technological change, poor infrastructure and scanty market information (Gockel and Akoena, 2002; Otengo et al., 2015). Sacerdoti (2005) highlights that surveys and studies conducted across the world over different time periods provide compelling evidence that a vast number of small businesses fail in the first few years.

One of the major difficulties SMEs face is the issue of access to finance. The problem of SMEs access to finance has received wide recognition in academic literature (Abor and Biekpe, 2006). SMEs, especially in developing countries, suffer from lack of access to appropriate funds from both the money and capital markets (Chadhliwa, 2015). This is due in part to the perception of higher risks associated with SMEs (Kirschenmann, 2016). According to Eyiah and Cook (2003), access to finance is the most critical of all the numerous challenges facing small and medium scale contractors in Ghana and this has limited their active participation in construction activities. At least, it prevents contractors from satisfying the financial requirements (e.g. bid and performance bonds) necessary to secure projects, and procuring the other resources such as managerial and technical expertise. The lack of managerial know-how places substantial constraints on the development of the SME sector (Bouazza et al., 2015). SMEs tend to attract motivated managers, but hardly able to compete with larger firms. The paucity of management talent, prevailing in most countries in the region, has a magnified impact on SMEs (Abor and Quartey, 2010).

Regulatory constraints also pose serious challenges to SME development and although wide ranging structural reforms have led to some improvements, prospects for enterprise development remain to be addressed at the firm level (Abor and Quartey, 2010; Chadhliwa, 2015).

5. LEAN CONSTRUCTION

According to Mastroianni and Abdelhamid (2003), construction contractors are continually searching for ways to eliminate waste and increase profit with the continuous decline in profit margins and increased competition in the industry. Although various methods have been advanced to improving efficiency and effectiveness of construction processes, lean construction techniques offer the potential to minimize, if not entirely eliminate, non-value adding activities (Salem et al., 2006). Lean construction is a production philosophy, which has the potential of bringing innovative changes in the construction industry (Sage et al., 2012). Successful application of lean principles leads to an improvement in cost, productivity, plan reliability, quality, and job satisfaction (Salem et al., 2006; Cho and Ballard, 2011).

Lean construction practices have developed quite well over the last few decades and have lived up to their potential in many different countries (Raghavan et al., 2014). In recent times lean construction has attracted a lot of attention in the industry as it tends to increase construction process reliability, reduce total lead times and improve the quality of projects produced (Sacks and Goldin, 2007). The implementations of lean tools within developed and emerging countries have shown positive results in improving the performance of projects (Ballard et al., 2009). Despite the benefits of Lean construction, research has shown that SMEs face significant difficulties when implementing the system (AL-Najem, 2014). These challenges cannot be overcome unless SMEs are supported in adopting the lean philosophy. This can be achieved by building SMEs' capacity as they lack the needed capacity to fully adopt the lean system.

6. FACTORS LILMITING SMEs CAPACITY IN LEAN CONSTRUCTION ADOPTION

There have been several efforts in exploring opportunities for implementing many management approaches such as information management (Love and Irani, 2004) and innovation (Barrett and Sexton, 2006) within SMEs in the construction industry. According to Shang (2013), most of these studies show that due to the limited resources of SMEs, they are more focused on securing the next project, rather than on implementing contemporary management approaches such as Lean Construction. According to Ghobadian and Gallear (1997), SMEs are reluctant to accept Lean, and this can be attributed to factors such as lack of resources, lack of skilled people, and ineffective relationships with suppliers – the opposite of which is required to succeed in Lean.

Generally speaking, small firms pay less attention to strategic human resource management (De Kok and Uhlaner, 2001). Many SMEs think of staff as a kind of cost other than a resource. Human resources in SMEs are weak in terms of their knowledge and skills. There are a number of issues that affect SMEs' ability to recruit, motivate and retain the best of talents (Darkwah, 2014). This affirms Gockel and Akoena (2002) assertion that small and medium sized construction companies have less adequate management skills and limited personnel in terms of both availabilities and abilities. Inadequate human resource capabilities are a major constraint in lean adoption as lean requires a multi-skilled workforce who are motivated and empowered to work (Gao and Low, 2015). SMEs face enormous difficulties in the implementation of Lean, including financial constraints and limitations in other needed resources (Ghobadian and Gallear, 1997; Achanga et al., 2006). SMEs are generally constrained by their sizes, and lack of technical expertise, managerial time, financial resources, and human resources, which affect their Lean efforts (Achanga et al., 2006; Panizzolo et al., 2012).

The success of lean lies in the commitment of top management and buy in by the top management (Al-Najem et al., 2012), but it is more difficult for top management in SMEs to acknowledge the need for change. This can be attributed to factors such as their limited resources, pressures on top management and style of management (Ghobadian and Gallear, 1997). Introducing lean requires cultural change (Abrahamsson and Isaksson, 2012) at different levels within the organisation, and top management needs be aware of this (Gao and Low, 2015). In essence, it is difficult to succeed in lean construction without a healthy culture. In UK for instance, only 10% of the firms succeed in their lean implementation efforts. The reasons for such a huge failure are culture and management (Taleghani, 2010). Lean construction requires a culture of employee empowerment, teamwork and enhanced relationship with suppliers. This is mostly lacking within SMEs, as employees are not usually empowered and relationship with suppliers is mostly adversarial. Top down leadership style that is a characteristic of Construction SMEs is one of the many cultural barriers that cause lean initiatives to fail.

7. KNOWLEDGE GAP ANALYSIS OF LEAN CONSTRUCTION ADOPTION WITHIN SMEs

Lean has increasingly been recognised as a key improvement concept for all types of organisations to enhance their operations. Several studies (Salem et al., 2006; Cho and Ballard, 2011; Bhamu and Sangwan, 2014) point to the significant benefits of lean construction to the problems of low productivity, low quality, increased cost, low job satisfaction and waste generation within construction process. Notwithstanding the substantial impact of Construction SMEs on the general performance of the construction industry, and the importance of this sector to economic growth, much effort, with initiatives such as lean thinking, have been and continue to be concentrated on LEs to the neglect of SMEs (Ayarkwa et al., 2012; Shang, 2013; Filho et al., 2016). This makes Lean an under-researched area in the context of SMEs (Tezel et al., 2017). Currently, there is no standard model for Lean implementation that SMEs can adopt (Rose et al., 2011). It appears, however, that there is a significantly lower uptake of Lean in SMEs compared to LEs (Shah and Ward, 2003), and that many SMEs are still unfamiliar with Lean implementation (Achanga et al., 2006). Previous works have fallen short of looking at how SMEs' capacity can be built to fully implement the lean philosophy. There has also been many capacity building initiatives for construction SMEs (for eg. Orhin, 2014; Asante, 2015; Offei, 2015), but little has been done in terms of building the capacity of Construction SMEs to adopt lean.

8. THE NEED FOR CAPACITY BUILDING OF SMEs FOR LEAN CONSTRUCTION ADOPTION

SMEs are constrained in terms of resources (Marasini et al., 2014; Netland, 2016). Accordingly, lean implementation has become a challenge for SMEs (Marasini et al., 2014). This has led to a concentration on what SMEs can and should do within their available resources. In the work of Rose et al. (2011), it was argued that SMEs should go in for least costly tools, which is well within their capacity. In another work, Matt and Rauch (2013) suggested that SMEs should use tools and practices affirmed to be suitable for them. However, in most cases the use of isolated practices fails because those practices do not address both the social and the technical parts of the organization (Lathin and Mitchell, 2001).

Lean requires new knowledge and cultural change during the transition and it should be applied comprehensively and holistically in principles and concepts (Liker, 2004). The benefits of a full implementation cannot be compared with an implementation of just a few tools (Liker, 2004; Netland, 2016). The lack of resources within SMEs makes it even more imperative to adopt lean construction as lean gives more value with minimal resources.

Shang (2013) proposed an implementation framework for large Chinese construction companies. The reason was that large construction firms are more likely to absorb the lean philosophy than SMEs. Similarly, in a study conducted in Ghana by Ayarkwa et al. (2012), it was also suggested that SMEs do not have the capacity to implement lean construction. Implementing lean can lead to substantial benefits to any organisation whilst the cost of not being able to implement such management approach may be very significant. In spite of the significant contributions construction SMEs make to the economies of both developed and developing nations, they face a lot of challenges that affect their capacity (Amoah et al., 2011). A successful adoption of lean by construction SMEs will heavily depend on their capacity for easy implementation. From previous studies, it can be said that SMEs' capacity is inadequate to fully implement the lean philosophy. Therefore, there is a clear need to build the capacity of construction SMEs to fully implement the system, because Lean construction is also aligned to SMEs needs for tangible results (Abbot and Aziz, 2015).

Studies conducted within the Ghanaian construction industry suggest a low level of familiarity and application of lean construction among practitioners within the industry (Ayarkwa et al., 2012; Ankomah et al., 2015). A number of obstacles have also been identified as possible challenges against the implementation of lean construction (Ayarkwa et al., 2012). Little empirical work, if any, therefore exists on lean construction capacity building for Construction SMEs, which is seen as the engine of growth for economies worldwide. Comparatively, construction SMEs are unimportant in terms of output, although they constitute majority of firms. Consequently, any improvement effort in SMEs will impact greatly on the performance of the whole industry (Gyadu-Asiedu, 2009).

9. CONCLUSION

SMEs are commonly recognised as being critical to the health of the global economy. Thus, the development of the SME sector is of paramount importance to any country irrespective of its level of development. Their relevance and importance can be realized in all aspects of the socioeconomic lives of countries such as job creation, poverty reduction, and spreading development to all parts of countries especially in the rural areas. Notwithstanding these attributions, SMEs are faced with fundamental problems. These problems adversely affect organizational production and processes, leading to defects, high cost, safety issues, customer dissatisfaction, decreasing competitiveness, etc. This, in effect has led to widespread underperformance and a high attrition rate amongst SMEs. Lean is recognised as a management philosophy to help organisations to be effective, efficient and maximize value to clients. Therefore, the adoption of Lean is an important area to examine, especially as there is a lower up take of Lean by SMEs. The success of lean is no secret to practitioners, but it is still difficult to emulate especially for SMEs. The paper has justified that SMEs lack the needed capacity in terms of human resources, finances, organisational culture and the skills and expertise to fully implement the lean philosophy. In their quest to become lean, SMEs have used isolated tools and practices. However, the use of these isolated tools and practices fail because lean is a system that has to be implemented in a holistic manner. This study has shown clearly that there is the need for capacity building of construction SMEs to adopt Lean construction. The benefits of implementing Lean are substantial while the cost of not being able to meet project goals may be very significant. This serves as a basis for an ongoing PhD, which aims at developing a framework for capacity building of Small and Medium Building Contractors for lean adoption to enhance their performances.

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