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I. QUALITY CONTROL AND MANAGEMENT (A1)

Registration-free 3D Point Cloud Data Acquisition Technique for as-is BIM Generation Using Rotating Flat Mirrors

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Abstract: Nowadays, as-is BIM generation has been popularly adopted in the architecture, engineering, construction and facility management (AEC/FM) industries. In order to generate a 3D as-is BIM of a structural component, current methods require a registration process that merges different sets of point cloud data obtained from multiple locations, which is time-consuming and registration error-prone. To tackle this limitation, this study proposes a registration-free 3D point cloud data acquisition technique for as-is BIM generation. In this study, small-size mirrors that rotate in both horizontal and vertical direction are used to enable the registration-free data acquisition technique. First, a geometric model that defines the relationship among the mirrors, the laser scanner and the target component is developed. Second, determinations of optimal laser scanner location and mirror location are performed based on the developed geometrical model. To validate the proposed registration-free as-is BIM generation technique, simulation tests are conducted on key construction components including a PC slab and a structural wall. The result demonstrates that the registration-free point cloud data acquisition technique can be applicable in various construction elements including PC elements and structural components for as-is BIM generation.

Key words: registration-free, 3d point cloud, data acquisition, laser scanning, as-is BIM generation

1. INTRODUCTION

As-is BIM model is defined as the as-is condition digital model involving 3D geometry information and 3D visualization of a construction project [1]. A project may not be constructed as its design, changes are required during sequence renovations, which points to the need for as-is BIM generation. On the other hand, it is also necessary to implement as-is BIM applications for an existing building in the O&M phase when the BIM model is missing or out-of-date. With the development of remote sensing technologies, point cloud data collection by laser scanner is an accurate and efficient way to create an as-is BIM model in the construction industry. This is because 3D laser scanning can rapidly and accurately measure the 3D shape of the target object [2]. Many researchers have studied and proposed diverse as-is BIM generation methodologies and approaches. There are two main trends of the research related to as-is BIM generation, namely as-is BIM generation with as-design model and as-is BIM generation without as-design model. As for the as-is BIM generation with as-design model, researches focused on different scales of construction components from a single structural component to an overall building structure. Bosché et al. [3] proposed a robust approach to perform as-built BIM generation for the column by integrating the as-designed model and 3D laser scanning data. Valero et al. [4] established the geometrical relationship among the interior objects to develop an accurate 3D semantic as-is BIM

generation method for furnished office and home interiors based on as-is design model, which involved as-is BIM generation for both immobile structural element and mobile furniture. However, these studies showed that the performance of as-is BIM generation relied on the as-design model, which could not be applied to the project without the as-designed model in an accurate manner. Therefore, many researches have studied on as-is BIM generation without the aid of as-is design model to address this limitation. For example, Wang et al. [5] and Sanchez et al. [6] proposed automatic as-built BIM creation methods for planar building interiors and building envelops based on prior knowledge respectively, which was capable of generating simple models in terms of ceilings and floors without the as-design model.

However, in order to generate as-is model of a structure or component, those prior works require a registration process that merges different data sets obtained from multiple positions, which may be time-consuming and cost demanding. In addition, registration errors are inevitable due to the imperfection of the merge process based on targets or common features from different scans. To tackle these problems, this study proposes a novel registration-free as-is BIM generation technique. The proposed technique uses flat mirrors to scan the hidden surfaces of a target component from the view of laser scanner so that the entire surfaces (both visible and invisible surfaces) can be scanned without a registration process. In this way, scanning time can be reduced and registration error can be prevented. The rest of paper is organized as follows: First, section 2 reviews the current research about the data acquisition quality determination and scan planning. Then, the development of a registration-free data acquisition technique is illustrated in section 3, which includes the overall scheme and procedure of the proposed technique. Next, the proposed method is simulated on PC slab and a structural component respectively in section 4. Lastly, section 5 presented the conclusion and the contribution of the study.

2. LITERATURE REVIEW

It is important to ensure that point cloud data are acquired in the required quality in order to guarantee good performance of as-is BIM generation. So far, many studies on 3D data acquisition methods and scan planning have been conducted to achieve effective as-is BIM generation. Therefore, the sections below present the recent literature related to data acquisition quality and scan planning.

2.1. Data acquisition quality

There have been many criteria or guidance for data quality determination for as-is BIM generation. U.S. General Services Administration (GSA) [7] presented data quality requirements reflected by allowable dimensional deviation and the smallest recognizable features according to different applications of as-is BIM creation. In addition, the parameters evaluating the point cloud data quality have been discussed in previous research. Dai et al. [8] evaluated 3D point cloud data quality based on the three parameters including data density, tolerance and coverage completeness. As the most popular parameters for point cloud data quality evaluation, spatial density and tolerance are mainly influenced by the collecting parameters including angular resolution, incident angle and scanning range. Coverage measures the proportion of the target object covered by the point cloud data, which is important when occlusion among building components exist [9,10]. Besides the three parameters mentioned above, Wang et al. [10] proposed a scan-to-BIM framework with the consideration of the RGB color. In order to capture such properties, the scanning locations are required to be carefully located to ensure a line of sight from the laser scanner to the target component.

2.2. Scan planning

After determining the required data acquisition quality, scan planning is considered to use efficient 3D point cloud data acquisition. Soudarissanane et al. [11] proposed a method to determine optimal laser scanner locations by projecting the scene into a 2D map in order to simplify the process and reduce the computation workload. Tang et al. [12] developed a mathematical model between the collecting parameters and data quality to determine optimal parameters for 3D point cloud generation. The validation results showed all data points could satisfy the data acquisition quality requirement up to GSA level 3 within the data collection time of 6 minutes 40 seconds for each scan. Biswas et al. [9] presented a method to select the smallest set of scanner locations by an integer programming algorithm to achieve accuracy and coverage requirements. The proposed method was validated by conducting a scan planning on a concrete floor with a satisfaction precision of less than 2 mm and expected scan

coverage of more than 50%. Ahn et al. [13] reported an interactive scan planning position decision approach for heritage building with both analytic computation and heuristic decision. The experiment results showed that the proposed method can achieve optimal scanning location determination with required scanning range and incident angle. Argüelles-Fraga et al. [14] conducted the determinization of scanning locations for circular cross-section tunnels based on tunnel dimensions, scan density and footprint size. A validation test conducted on a tunnel (105m long) indicated that the interval distance among the different scanning locations should be properly selected because point cloud data quality was decreased as the scanning range increased.

Despite previous scan planning studies, these studies are mainly assumed that a complete 3D scanning is achieved with multiple scans at different locations. For this reason, a registration process is needed for merging multiple scans. However, scanning parameter determination is ignored for the registration-free technique. Hence, through the development of registration-free data acquisition technique proposed in this study, the collecting parameters determination including laser scanner location and mirror location decision is investigated for a comprehensive scan planning consideration.

In this study, registration-free data acquisition technique for as-is BIM generation using rotating flat mirrors and laser scanning is investigated firstly. Then, data acquisition for as-is BIM generation of the PC slab and a structural component are simulated based on the proposed technique.

3. TECHNIQUE DEVELOPMENT

3.1. Overall scheme of the registration-free 3D data acquisition technique

Figure 1 shows the overall scheme of registration-free data acquisition technique for as-is BIM generation using rotating flat mirrors and laser scanning. In this study, two components including precast concrete units and structural walls are targeted for investigation. First, for the PC slab as shown in Figure 1(a), 4 flat mirrors are positioned next to the side surfaces to reflect the hidden side surface from the laser scanner and achieve a registration-free point cloud generation of the entire surface of the PC unit. Here, the mirrors are aided by a goniometer to achieve rotation in horizontal and vertical direction in order to cover the end part of the side surfaces. Here, the mirrors rotate in the horizontal and vertical direction to cover the end part of the side surfaces. On the other hand, as for the structural element as-is 3D point cloud data acquisition, the proposed technique uses two flat mirrors to simultaneously scan a portion of the two hidden surfaces using the stationary flat mirrors as shown in Figure 1(b). Note that laser scanner beam has the same property with nature light that they can be reflected by the flat mirror. In addition, small sizes of flat mirrors are employed in the proposed technique based on the reasons that large-size mirror is easily broken and hard to be used in real off-site and on-site environment. Note that with these two scan configurations, there is no need for change in the laser scanner and mirror location during the scanning process, resulting in a registration-free approach without changes in the laser scanner position.

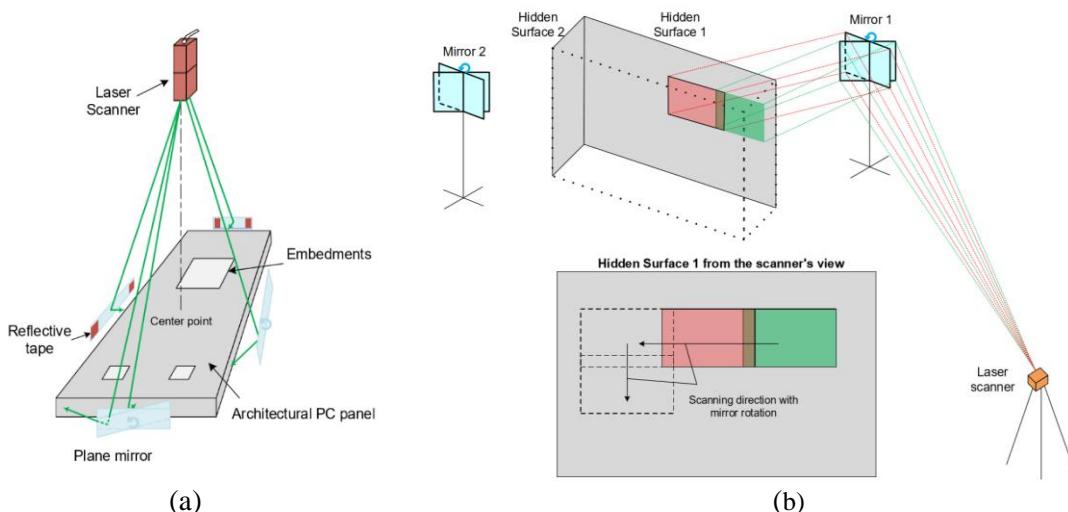


Figure 1. Overall scheme of registration-free data acquisition technique using rotating flat mirrors and laser scanner on: (a) PC element and (b) construction components (e.g. structural or internal wall)

3.2. Procedure of the registration-free data acquisition technique

Figure 2 shows the detailed procedure for the registration-free data acquisition technique. There are five primary steps that are 1) mathematical relationship model development, 2) scanning route planning, 3) laser scanner location determination, 4) mirror location determination, and 5) data acquisition execution for as-is BIM generation.

First, a mathematical model that represents the geometrical relationship among the laser scanner, mirrors and target object is developed. Then, scan route planning is performed to determine the direction and technical details of scanning using the flat mirrors that reflect laser beams on the hidden surface. Once the two key basic steps are conducted, an optimal laser scanner location is selected based on the evaluation of data quality on visible surfaces. Next, mirror location is then determined by finding the location which allows for minimum scanning time. Finally, a set of point cloud data on the entire surface of the target object is collected for as-is BIM generation

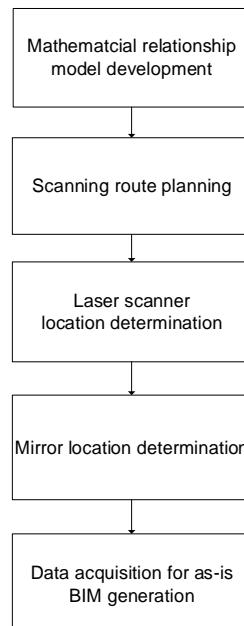


Figure 2. Primary steps of registration-free point cloud data acquisition technique for as-is BIM generation

3.2.1 Mathematical relationship model development

This step aims to understand and develop a geometrical relationship model that represents the relationship among the laser scanner, mirrors and hidden surfaces of the target object. Figure 3 illustrates the input-output diagram of the mathematical relationship model. The input parameters of the model are the laser scanner location, mirror plane and hidden surface plane of the target object. To be specific, the parameters of the mirror plane include 1) the mirror plane normal vector, 2) the centre point of the mirror and 3) four mirror corner points. Meanwhile, the parameters of hidden surfaces are 1) the hidden surface normal vectors and 2) the centre point of the hidden surfaces. The output of the relationship model includes 1) the four points reflected by the four mirror corner points and falling on the hidden surfaces and 2) the scanning area generated by the four output corner points. Note that the four corner points are calculated according to the mirror reflection principle. The details are shown as following: The laser beam emitted from the laser scanner is reflected by the mirror corner point and reaches the point on the hidden side surface of the target object. However, the laser scanner generates the coordinates of the virtual scan point on virtual side surface based on the assumption that the laser beam travels in a straight line. The 3D coordinates of the corner points on hidden surface is then calculated according to the geometrical relationship that virtual scan point and the corner point on hidden surface is symmetric with respect to the mirror. Note that the scan route planning, that is the next process, can be conducted using the output information of the mathematical relationship model.

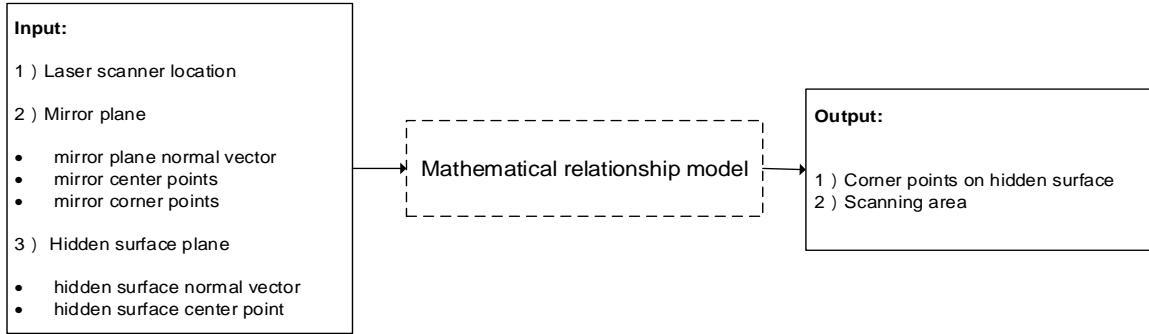


Figure 3. Input-and-output diagram of the mathematical relationship model

3.2.2 Scanning route planning

This step aims to plan the scanning route to be scanned by the rotating mirror on the hidden surface in order to achieve a complete scan on the hidden surface. Figure 4 shows the proposed scan route planning on a hidden surface. This study assumes that scanning is conducted from the bottom to the top of the hidden surface. First, the scanning route named ‘1st horizontal route’ is conducted along the bottom line of the hidden surface by changing the mirror angle. To do this, there are two constraints used in this study. First, two side boundaries and the bottom boundary of the hidden surface should be covered in the ‘1st horizontal route’. Second, there should be a certain amount of overlap between any two adjacent scans with different mirror angles. Once the bottom horizontal route is completed, a new boundary for vertical route and a new horizontal route is updated. The updated bottom boundary is parallel to the previous bottom boundary and covers the lowest scan point generated from the previous scanning route (‘1st horizontal route’). Then, a new scan covering the update bottom boundary and the side boundary near the last scan of the previous horizontal route is generated, resulting a vertical route in order to increase the scanning level. Next, a new horizontal route (‘2nd horizontal route’) is generated with the consideration of the two constraints mentioned before. Finally, the scanning level is increased until full hidden surface scan is achieved through the horizontal route and vertical route scan. It is noted that this step only provides scanning route and the number of scans will be determined once the locations of the laser scanner and the mirror are selected. Also, the number of scans is affected by the other parameters including mirror size and the overlap threshold.

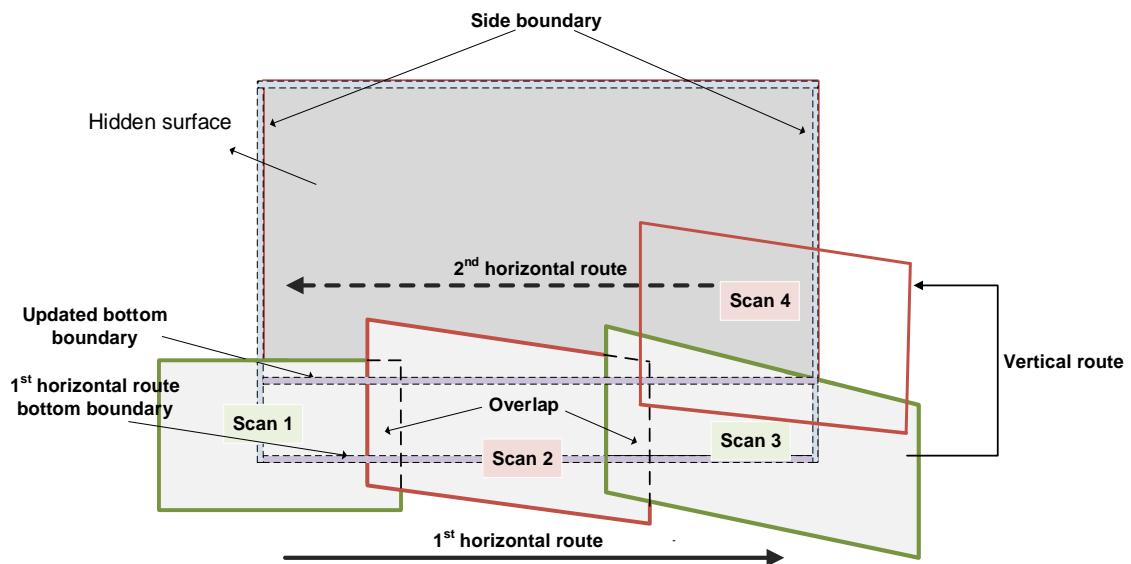


Figure 4. Scanning route planning

3.2.3 Laser scanner location determination

This step aims to select an optimal laser scanner location by finding the location where the best scan data quality on the visible surfaces of a target object is achieved. In terms of scan data quality, three criteria related to 1) visible surfaces, 2) feature points and 3) point-to-point distance, are used. First, visible surfaces of the laser scanner should be maximized. For example, there are one and two visible

surfaces for the cases of Figure 1(a) and 1(b), respectively. Second, feature points defined as the key geometric features of the target objects should be captured. For instance, corner points of the top surface of Figure 1(a) are the feature points that should be captured. Third, the optimal scan location should meet the requirement for point-to-point distance defined as the distance between two adjacent scan points. Table 1 shows the requirements of point-to-point distance with varying target objects set by the GSA [7] for as-is BIM generation. For example, a large point-to-point distance of 25 mm (sparse scan data) is required for the data acquisition of building exteriors while a low point-to-point distance of 13 mm (dense data) needed for building interior components (e.g. floor level, room and artifact) [7,14].

Table 1. Data Quality and Requirements Standardized by GSA [7]

GSA Level	Area of Interest	Point-to-Point Distance
1	Total project area	152 mm
2	Subsection of Level 1 (e.g building)	25 mm
3	Subsection of Level 2 (e.g floor level)	13 mm
4	Subsection of Level 3 (e.g room or artifact)	13 mm

The process of selecting the optimal laser scanner is presented as follows. First, potential scanning locations are generated in 2D grid with a user-defined grid distance. Note that small grid size will generate more potential scanning locations for determination but increases the computation workload, so the grid size should be properly decided according to the two considerations above. Here, the intersections of the grids are regarded as potential scanning locations for the laser scanner position. Second, potential scanning positions that meet the two criteria 1) feature points and 2) point-to-point distance are determined. Note that feature points may have multiple point-to-point distances because they can be the intersection points of surface edge lines with different directions. In this case, it is required that all point-to-point distances should meet the requirement set by the GSA. If there is a featured point of a potential scanning location fails to satisfy the point-to-point distance condition, the potential scanning location is eliminated and not considered as the optimal location. Third, calculation of the degree of meeting the point-to-point distance requirement is performed for the remaining possible scanning locations. To do this, a scoring metric named '**FP Score**' is used to compute the degree of suitability. The '**FP Score**' of each feature point (P_i) is defined as:

$$\text{FP Score}(P_i) = \sum_{j=1}^m \frac{D_{\text{required}} - D_{\text{measure}}(j)}{D_{\text{required}}} \quad (1)$$

Where D_{measured} and D_{required} refer to the point-to-point distance measured, and the maximum point-to-point distance required, respectively. Also, m stands for the number of point-to-point distance that a feature point has. Next, the suitability of each remaining scanning location is computed. Here, the location suitability score named '**SP score**' of each potential scanning location (L_i) is calculated as:

$$\text{SP score}(L_i) = \sum_{k=1}^n \text{FP Score}(p_k) \quad (2)$$

Where n refers to the number of featured points. Finally, the optimal scanning location with the highest '**SP score**' is determined as the laser scanner location.

3.2.4 Mirror location determination

First, mirror size is determined by considering scanning site physical constraints. Second, 3D grids with a user-defined resolution are generated behind the hidden surface of the PC element within the available scanning area, and the intersection points are set as potential mirror centre locations. Third,

similar to the laser scanner location selection process, the removal of mirror locations based on the two conditions that are 1) mirror locations are invisible from the laser scanner; and 2) mirror locations have not enough space for mirror rotation. Fourth, for the remaining potential mirror locations, the number of scanning along the planned scanning route mentioned in Section 3.2.2 is computed for each potential mirror location. As the final step, the optimal mirror location is selected as the location having the minimum number of scanning.

3.2.5 Data acquisition for as-is BIM generation

Once the laser scanner location and mirror location are determined, 3D point cloud data of the target component is collected along the planned scanning route. In this way, the laser scanner consecutively scans a portion of the hidden surfaces to cover both the visible and invisible surfaces surface of the target component without changing the scanner location, resulting in a registration-free scan data acquisition for as-is BIM generation.

4. VALIDATION

In order to validate the proposed registration-free scan data acquisition for as-is BIM generation, a series of simulation were conducted. Figure 5 shows the size of a PC slab and an interior wall used for the simulation. The PC slab and the interior wall have the dimensions of 1200 mm (length) \times 500 mm (width) \times 300 mm (height) and 2000 mm \times 300 mm \times 2500 mm, respectively. According to Table 1, the target objects, PC slab and interior wall, are under the GSA level 4 so that the required point-to-point distance (**D-required**) is less than 13 mm. Also, the angular resolution of 0.036° was used for calculating the measured point-to-point distance (**D-measure**).

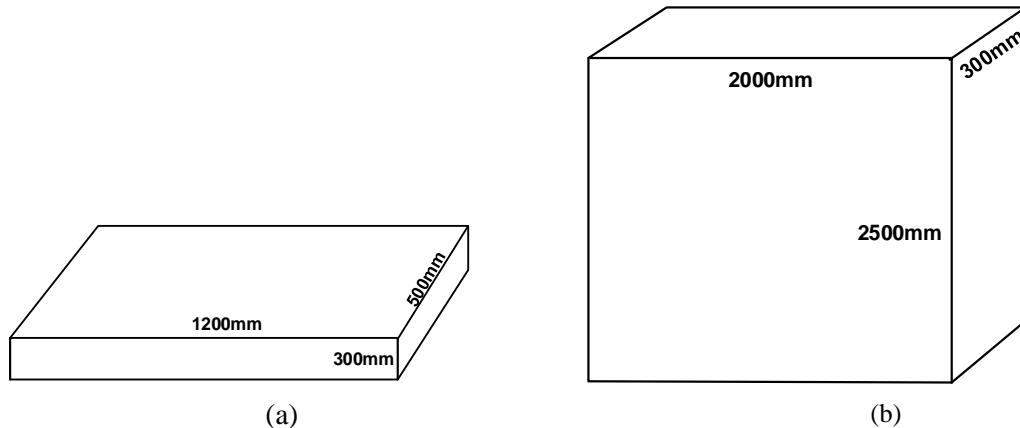


Figure 5. Dimensions of target components for simulation: (a) PC slab and (b) Interior wall

4.1. Simulation on PC element

For the simulation of the PC slab, the laser scanner height was selected as 1.2 m which is higher than the PC element in order to cover the three visible surfaces. A user-defined size of grid 0.1 m \times 0.1 m was used for generating potential laser scanning locations, resulting in the creation of 496 potential scanning locations. Based on the two criteria related to feature point and point-to-point distance, 372 potential locations which fail to meet the two criteria were filtered out. Next, the performance of the remaining 124 laser scanner locations was computed based on Eq. (5) and the location of (1.7m, -1.1m, 1.2m) respect to the left-bottom corner point of the PC slab was selected as the optimal scanning position. Figure 6 shows the result of the determination of the optimal laser scanner location. Note that the points in gray color refer to the scanning locations filtered out and the remaining scanning locations are provided with different colors. In the figure, warmer color point refers to higher suitability for laser scanner location.

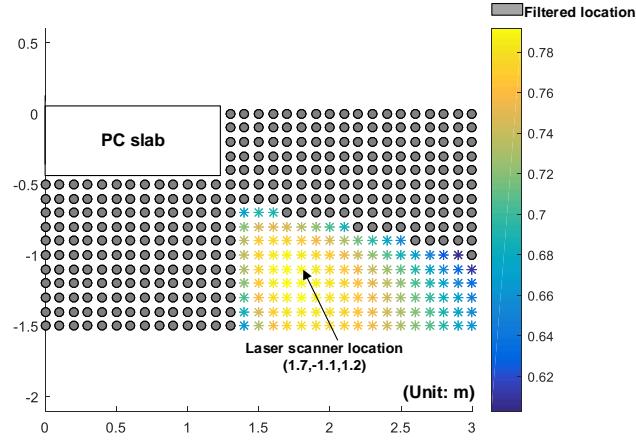


Figure 6. Result of laser scanner location determination. Here, warmer color point refers to higher suitability for laser scanner location

After the selection of the laser scanner location, the mirror location decision was conducted by finding the location with the least scanning time in 3D grid. For the PC slab with two hidden surfaces, two mirror locations are required to be used. Based on the consideration of scanning site physical constraints, the mirror size was set as $0.3\text{m} \times 0.3\text{m}$. As for the longitudinal hidden side surface, a 3D grid with a size of $0.4\text{ m (length)} \times 0.4\text{ m (width)} \times 0.15\text{ m (height)}$ is first generated on behind of the longitudinal hidden surface of PC slab for potential mirror centre locations, resulting in 72 potential mirror locations. Then, 30 mirror locations were filtered out according to the criteria and 42 potential mirror centre locations are used to calculate the number of scans to achieve a complete scanning on the hidden surface. From the computation, the location of $(1.6\text{ m}, 0.8\text{ m}, 0.45\text{ m})$ was selected as the optimal mirror location having the least scanning time. The mirror location for transversal side surface was then determined in the same method. The mirror size was set as dimensions of $0.3\text{m} \times 0.3\text{m}$ and 3D grid size was set as $0.4\text{m} \times 0.4\text{m} \times 0.15\text{m}$, which were same as the setting for longitudinal side surface. There were 72 mirror locations generated and 17 mirror locations were filtered out according to the two criteria. For the remaining 55 mirror locations, the optimal mirror center location was selected as the location with the least scanning time for hidden transversal side surface scanning, which is at the coordinate of $(-0.4\text{m}, -0.9\text{m}, 0.15\text{m})$. Figure 7 shows the determined laser scanner location and mirror location for PC slab.

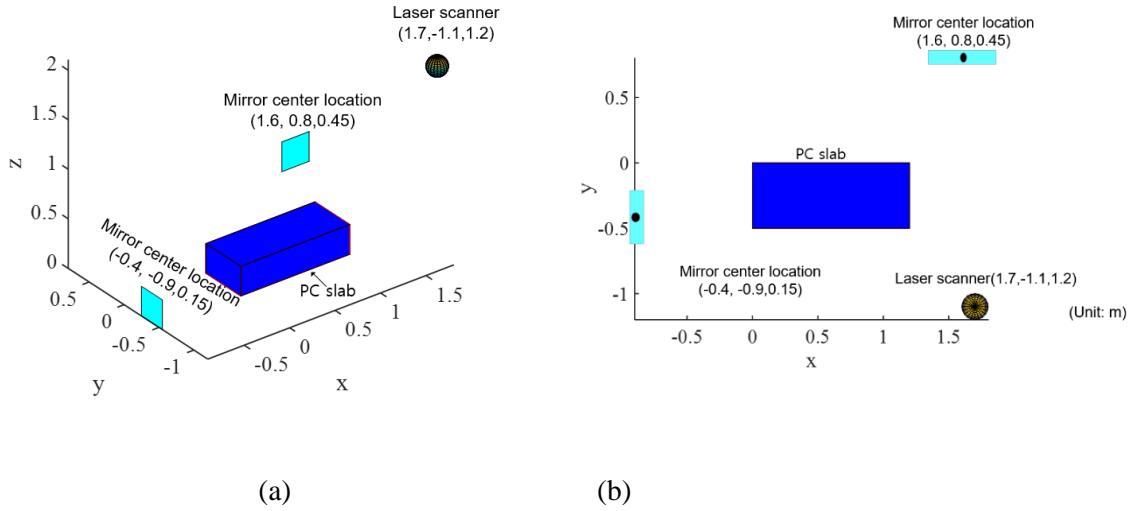


Figure 7. Determined laser scanner location and mirror location for PC slab:(a) 3D view and (b) 2D view.

4.2. Simulation on wall

This section simulates the proposed registration-free data acquisition on wall for as-is BIM generation. First, the user-defined laser scanner height was set to be 1.5m which was lower than the

wall. Then, the grid generated in 2D for finding the optimal laser scanner location was defined as the size of $0.1\text{m} \times 0.1\text{m}$. 961 potential locations were generated in this way and 807 scanning locations were filtered out according to the conditions defined in section 3.2.3. After evaluating the performance of the remaining 154 scanning locations, the optimal lasers scanner location was selected as the location with the best performance, which was at the coordinate of (3m, -1.8m, 1.5m). After deciding the laser scanner location, mirror center location for hidden surface scanning was defined as follows. It was assumed that one transversal side surface of the wall was connected to the other structural components (e.g. another wall that is perpendicular to this transversal side surface) of the building. Therefore, only one longitudinal side surface was required to be scanned. First, the mirror size was set as a size of $0.6\text{m} \times 1.2\text{m}$ and 3D grid size was set as $0.25\text{m} \times 0.5\text{m} \times 0.2\text{m}$. Then, 153 mirror center locations were generated in 3D grid. After the filtering, 36 potential mirror center locations were filtered out. The optimal mirror center location was selected as the location with the least scanning time for hidden transversal side surface scanning, which was at the coordinate of (2.5m, 2m, 1.6m). Figure 8 shows the determined laser scanner location and mirror location for the wall.

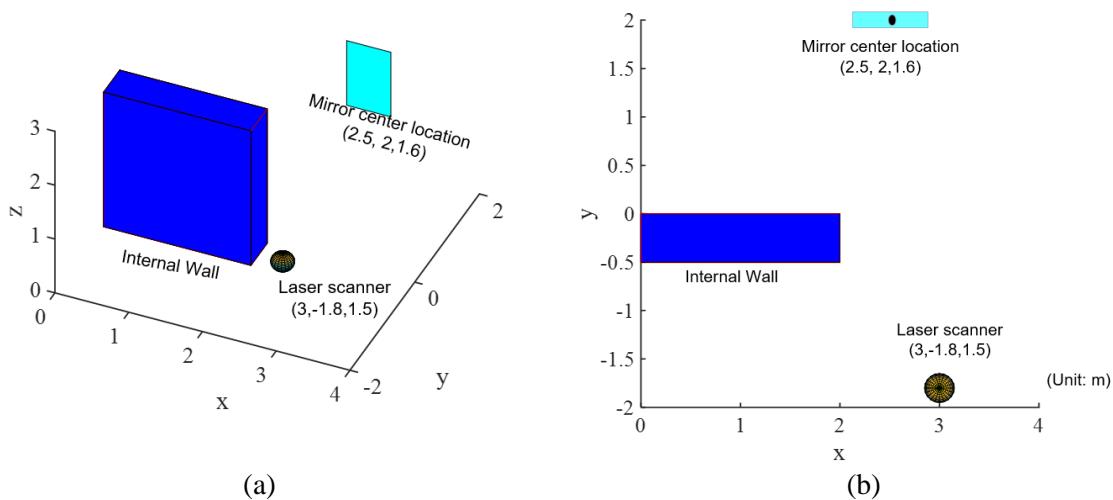


Figure 8. Determined laser scanner location and mirror location for wall: (a) 2D view and (b)3D view.

4.3. Discussion

In this study, the potential locations for both laser scanning location determination and mirror location determination are generated with a user-defined gird size. The selection of small size grid is likely to generate more potential locations with low resolution but increase the computation load. In this way, the grid size should be properly selected according to the two considerations. In addition, the mirror size is also determined with a user-defined value according to the physical site constraints in this study. However, the selection of the mirror size has influence on the performance of the complete hidden surface scan, which requires more comprehensive investigation in future study.

5. CONCLUSION

This paper presented a registration-free 3D point cloud data acquisition technique for as-is BIM generation. The proposed technique uses flat mirror which can rotate in both horizontal and vertical way to scan the side surfaces of target components. In this way, the entire surfaces of target components are scanned without registration process. which prevents registration-error and reduce scanning time. To develop the proposed method, five key steps are introduced in this study, which are mathematical relationship development, scan route planning, laser scanner location determination, mirror location determination and data acquisition. Though the simulation tests based on the data acquisition technique, it is concluded that the proposed technique has potential to be applied to various construction elements including PC elements and structural components onsite. This research improves the effectiveness of

data acquisition technique by developing a registration-free method, which contributes the as-is BIM generation of various construction components. However, the mirror size selection and gird generation for optimal scanning location and mirror location in this study relies on a manual way. Therefore, future work will focus on the automatic system creation for mirror size and location determination.

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A Framework for Automated Formwork Quality Inspection using Laser Scanning and Augmented Reality

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Abstract: Reinforcement steel fixing is a skilled and manually intensive construction trade. Current practice for the quality assessment of reinforcement steel fixing is normally performed by fabricators and has high potential in having errors due to the tedious nature of the work. In order to overcome the current inspection limitation, this study presents an approach that provides visual assistance and inspection enhancement for inspectors to assess the dimensional layout of reinforcement steel fixing. To this end, this study aims to establish an end-to-end framework for rebar layout quality inspection using laser scanning and Augmented Reality (AR). The proposed framework is composed of three parts: (1) the laser-scanned rebar data processing; (2) the rebar inspection procedure integrating with AR; and (3) the checking and fixing the rebar layout through AR visualization. In order to investigate the feasibility of the proposed framework, a case study assessing the rebar layout of a lab-scaled formwork containing two rebar layers is conducted. The results of the case studies demonstrate that the proposed approach using laser scanning and AR has the potential to produce an intuitive and accurate quality assessment for the rebar layout.

Keywords: rebar fixing, rebar layout inspection, laser scanning, Augmented Reality(AR), formwork inspection

1 INTRODUCTION

Reinforcement steel fixing in reinforced concrete (RC) structures is a skilled and labor-intensive construction task where there has not been much improvement in productivity over many decades. The task of fixing reinforcing bars named ‘rebar’ requires the ability to read 2D reinforcement drawings, mentally visualize the cage and an assembly sequence in 3D. One of the important activities for the steel fixing task is to check the number, dimensions, and locations of rebars as those dimensional properties dictate the structural performance and constructability of the RC structure. Current inspection on rebars and its formwork are carried out by qualified manufacturing or site engineers to check the dimensional compliance with national or international standards alongside project construction tolerance specifications. Although the rebars are expected to be placed the same as the dimensions and locations of the design drawings, precise rebar positioning is difficult to achieve even in a manufacturing environment. Therefore, there are specific tolerances set for several key rebar checklists to be inspected. The dimensional checklists for the rebars include 1) bar-to-bar spacing between rebars, 2) concrete cover and 3) the number of rebars. The primary issue of the dimensional inspection on rebars is that the task is a highly repetitive and time and cost demanding job due to the manual inspection by human workers. In addition, walking in the top rebar cages and climbing on vertical cages are common issues that can cause potential safety hazards for the inspectors and damage the integrity of the structure. Therefore, an

automatic rebar inspection technique that achieves a quick and accurate dimensional inspection on rebars is necessary.

Laser scanners have been one of the most popular recent measurement tools in the construction industry. Thanks to the fact that laser scanning provides high inspection accuracy (typically 2–6 mm at 50 m [1]) and high measurement rate (up to 960,000 points/s), many researchers have investigated the effectiveness of using laser scanning for dimensional quality inspection in the construction industry. In terms of dimensional quality inspection during the manufacturing stage, the target objects of previous studies were post-production prefabricated components such as precast slabs [2-4] and precast girders [5]. However, since it is costly to repair miss-manufactured components after production, it is also more important to check the dimensional qualities of formwork and its rebars prior to concrete casting. However, little attention has been paid on the dimensional quality inspection of formwork and rebar during the manufacturing stage.

Other than accuracy on dimensional quality checking, intuitive information visualization for quality inspection is also important. As an emerging technology, Augmented Reality (AR) delivers virtual information to the real world, further enhances the interpretability of many domain-specific applications in the construction industry, including construction safety, facility management, operation training, and inspection [6-7]. There is little research effort put on using AR as a measurement tool directly for dimensional quality inspection of construction components. The main reason is that the nature of positioning approaches based on images has not yet reached the level of accuracy compared with conventional surveying techniques. Furthermore, AR input interfaces to be used on-site in handling detailed measurement results maybe not investigated comprehensively. The functions on mobile or wearable devices are not as complete as those on general PC. Nevertheless, to visualize rebar or formwork fixing results using AR display is still desirable, as long as integration made with other measurement tools (i.e., laser scanners) can be relied on to simplify input and manipulation, and at the same time achieving accurate inspection purposes.

This study presents a systematic framework for automated formwork quality inspection using laser scanning and AR technology. This study aims to investigate the feasibility of the integration of the two technologies, and specific objectives are to 1) develop a framework that integrates laser scanning and AR for automated formwork and rebar inspection and 2) validate the framework through AR prototype development and laboratory experiment.

2 LITERATURE REVIEW

2.1 Rebar Dimensional Inspection

Regarding the rebar and formwork inspection, there have been few studies. Han et al. [8] proposed a vision-based technique that estimates the configuration and position of rebars. They used a density histogram of scan points generated from structure-from-motion and multi-view stereo algorithms for the rebar layout inspection. In that study, a validation test was performed using fifteen targets placed near or on the rebars and 850 images were taken for generating a set of point cloud data. However, the limitations of the study are that 1) detailed DQA results such as the overall dimension estimation accuracy are missing but focusing on data acquisition, and 2) numerous high-resolution photos are required from different angles for the generation of geometric data on the formwork and rebar. As an extension study of [8], Akula et al. [9] proposed a drilling monitoring and control framework that maps the locations of rebars within a bridge deck in order to provide timely feedback to the drill operator about whether it is safe to continue drilling based on the position and orientation of the drill. In that study, the same specimen used in [8] was used for generating point cloud data to map the locations of the rebar and the zones safe for drilling. A validation test was conducted on a lab-scaled rebar cage and the prediction accuracies from the vision-based technique were 69.5% while a terrestrial laser scanning (TLS) based method resulted in 98.4%. However, it was found in the study that 1) the vision-based technique requires a large number of images and the accuracy of the safe zone prediction is relatively low compared to the TLS approach, and 2) there was a large registration error caused by the targets placed near and on the rebars. On the other hand, Nishio et al. [10] proposed a method that extracts core wires of rebar from noisy scan data. A density distribution function was introduced to filter out unwanted scan points near the rebars and a parameter effect test was conducted by varying voxel sizes. However, the study was focused on only the extraction of rebar scan points. In addition, further analysis of the DQA checklists including the recognition and extraction of rebar spacing and the concrete cover is

missing. From the literature, there has been no study investigating the key DQA checklists including rebar spacing, formwork dimension and concrete cover during the fabrication stage.

2.2 AR Application for Inspection

AR technology can be used in facilitating the visualization of domain-specific information on-site, and previous research works also considered such technology in quality inspection applications [6, 14, 15]. In a tunneling construction, Zhou et al. [14] developed an AR-based displacement inspection approach and conducted a case study to prove its feasibility. According to the displacement tolerance, adjacent tunnel segments have to be installed close to each other with the displacement less than 5mm. They combined static images and AR to realize the quality evaluation of the segment placement tasks. Besides the static and careful adjustments, other approaches are also studied by researchers to improve the positioning accuracy of AR visualization. Tavares et al. [7] directly project the related BIM information onto steel frames through light beams for a welding alignment system. The technique is called Spatial Augmented Reality (SAR). The virtual information can be shown and observed through naked eyes, and accurate enough (under 3 mm) to identify the drilling positions on steel frames during manufacturing processes. SAR can be potentially implemented for dimensional inspection applications, while such projection is only useful on planar objects instead of the hallow structures like formwork and rebars allocated in it. As for the general usages of AR in dimensional inspection applications, it still not yet to be treated as a direct measurement tool. Feng et al. [16] have developed AR marker-based positioning algorithm and maintained the error of pose estimation within one inch (2.54mm). The experiment suggests that the proposed algorithm can achieve such a level of accuracy and even robust enough for detecting a target 10m away from the camera. However, the accuracy is not satisfied with certain requirements of dimensional quality of formwork and rebar arrangement. For instance, the errors of concrete depth measured by the distance between rebar and formwork top/bottom sides should be less than 9.5mm. Further enabling measurement tools need to be collaborated with AR visualization to achieve accurate and intuitive inspection. These include laser scanner [17], depth-sensing camera, RTK-GPS [6], projector [15] and so on. Despite the fact that enabling tools and integration strategies are getting mature, research works are rarely focused on the formwork and rebar dimensional inspection. Furthermore, the integrations of AR and enabling measurement tools to improve such critical inspection tasks lack a systematic framework to describe suitable work procedures. All these topics are worthy to be investigated in order to improve the current practice and address the tedious nature of the work.

3 INSPECTION FRAMEWORK

To develop an accurate and productive dimensional quality inspection on formwork and rebar fixing tasks, a framework with the integration of two enabling technologies, laser scanning and AR, has been proposed. As can be seen in Figure 1, the inspectors are involved in the loop of inspection with further inspection enhancement. Firstly, laser scanners can be used to acquire dimensional information of formwork and rebar arrangement. It is assumed that the inspection target is manufactured and the laser scanner is located on top of it where a comprehensive scan on inner-surfaces and reinforcements is possible. The laser scanned data (i.e., point clouds) can be stored in the database after a noise filtering and scoping process. Then the computer performs a series of processing, including formwork/rebar component recognition and dimension estimation. The resulting information can be further compared with the as-designed one stored as BIM models in advance, further identifying whether there is any discrepancy in between the manufacturing plan and actual product, which exceeded the tolerance of quality assessment. Once the list of the discrepancy is confirmed, it can be interpreted and downloaded to mobile devices for inspectors to conduct AR-based evaluation on the real target. The inspectors can not only perform their subjective visual inspections but also get the objective ones through AR display for their more accurate confirmation and fixing decisions. The scanning and AR-based inspection may be executed with the potential delay due to data transmission, processing, and comparison. Nevertheless, the inspection is able to be achieved efficiently, if the number of targets to be inspected are considered large. For realizing such a quality inspection flow, the following issues in terms of implementation should be addressed: (1) which scan parameter should be selected for dimension estimation; 2) how to visualize the analysis results via AR display, and 3) what kind of interface should be adopted for easy communications. The following section will elaborate on an implementation detail based on the proposed framework, including data processing, and AR visualization and guiding interfaces.

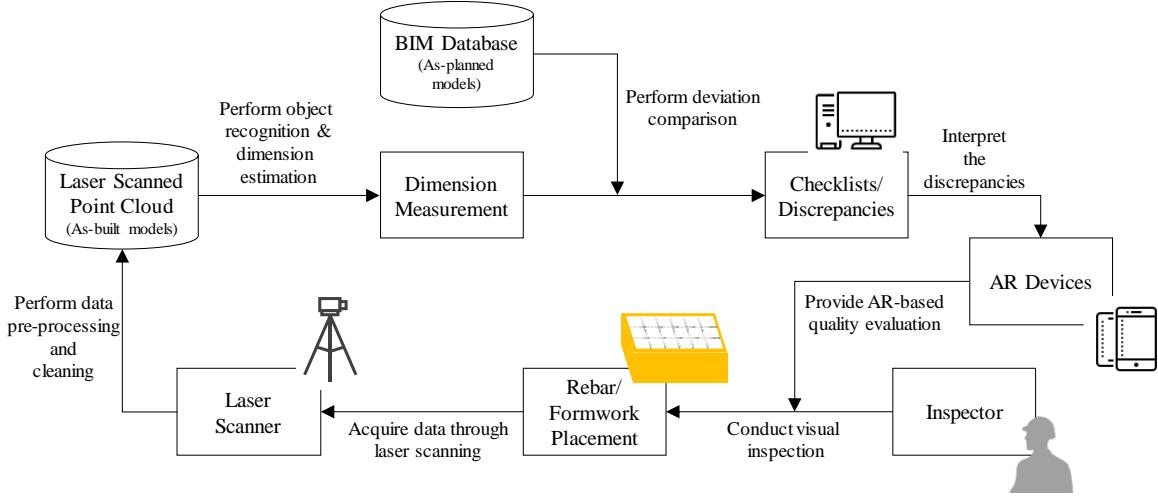


Figure 1. Overview of the proposed rebar fixing framework

4 SYSTEM DESIGN AND DEVELOPMENT

4.1 Data Acquisition and Processing

This section presents the data acquisition and processing details of the system. In this section, two layers rebars placed on the top and bottom on a formwork are taken as an example for the explanation.

4.1.1 Data Acquisition

An essential step of the data acquisition of laser scanning data is the selection of scan parameters of the laser scanner. This step aims to obtain the best data quality that achieves a highly accurate inspection result. For the scanning of rebar cage and formwork, the best scanning position would be the point where the laser scanner can see the rebar and formwork surfaces. For this reason, the scan position is an important aspect to be considered and selected because it influences the quality and completeness of the scanned points. Two factors need to be considered in identifying a proper scan position. Firstly, there should be no scan blocking issue. The bottom layer of the rebar needs to be captured well without line-of-sight blocking due to the top layer of the rebar. The other scan parameters including angular resolution and scan distance to the object mainly affect the data quality of scan data. Generally, the higher the density of scan points is, the better the inspection accuracy is. However, increasing the density of the scan points leads to increasing scan time and computing cost. Hence, a trade-off among accuracy, computing cost, and efficiency is necessary to be considered based on the inspection requirements of a project. The second factor is associated with high incident angle defined as the angle between a laser beam incident on a surface and the line perpendicular to the surface at the point of incidence. Because a high incident angle leads to an erroneous positioning of scan points due to a high range error, Kim et al. recommended avoiding scans with an incident angle of over 45° [2]. In addition, this high incident angle effect is much worse especially on the surfaces of smooth and metallic materials. Since identifying the best scan parameters for rebar cage specimens is a complex and challenging problem, it must be performed cautiously in advance, to maintain the high accuracy of the data acquisition process.

4.1.2 Data Processing

Once a set of point cloud data is acquired, data processing consisting of four steps is followed to extract dimensional features and then compute the key dimensions. The details of the four steps can be seen as follows:

Step 1 – Noise removal: This step aims to filter out unwanted background noises. First, raw scan data is sliced with respect to the Z-axis based on the fact that the key categories of scan data corresponding to ground noise, bottom formwork, bottom, and top layers are distinctly separable. Figure 2(a) shows

the result of the segmentation of five scan data elements that are (1) background noises; (2) bottom surface of the formwork; (3) bottom rebar layer; (4) top rebar layer and (5) top edge surface of the formwork. In order to remove the scan points of background noises, the multiple Otsu thresholding [11] is used based on the Z values of the scan data to generate thresholds.

Step 2 – Rebar and formwork recognition: This step aims to recognize the rebar and the formwork scan data. In order to recognize the scan data of the formwork surfaces (bottom and top edge surfaces and side inner surfaces), the bottom and top formwork planes are first estimated using the RANdom SAmple Consensus (RANSAC, [12]) algorithm. The inner surfaces of formwork are then estimated using the Principal Component Analysis (PCA, [13]). As for rebar scan data recognition, multiple line RANSAC is performed to identify both the transversal and longitudinal rebars in each layer. Figure 2(b) shows the recognition result of the formwork and rebar.

Step 3 – Feature point extraction and dimension estimation: Once each scan data set is recognized, feature points of the formwork and rebars are extracted. The feature points include 1) corner points of the inner side surfaces of the formwork that are obtained by intersecting the planes estimated in Step 2; and 2) center points of the sliced rebar section. Once the feature points are extracted, the key dimensions are computed. First, formwork dimensions including length, width and depth are computed using the intersection points. Second, the rebar spacing is estimated by calculating the distance between two adjacent rebar center points. Third, concrete cover is estimated by calculating the distance between one edge rebar surface and the bottom surface of the formwork. In addition, the number of rebars is computed the number of rebars recognized in Step 2. Figure 2(c) shows the result of dimension estimation.

Once the key dimensions are computed, discrepancies between the as-designed dimension and the as-built dimensions are calculated. If the discrepancy in rebar spacing for rebar is larger than the allowed tolerance, the rebar is recognized as a fault one, so spacing correction is needed. This recognition and correction are visualized in the proposed application which will be elaborated in the following subsections.

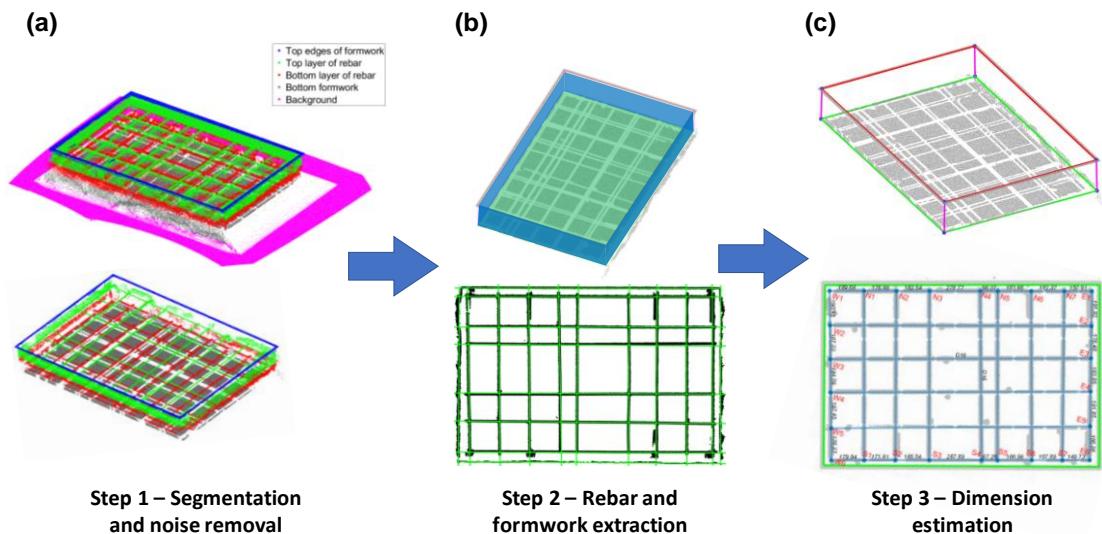


Figure 2. Data processing steps for rebar inspection

4.2 Inspector Application Development

An Android application, named AR Inspector, for dimensional quality inspection on formwork and rebar fixing tasks is developed in this study. It is developed based on a Game Engine, Unity3D, and its related AR package, Vuforia. The system architecture of AR Inspector consists of server-side databases with a processing unit, and a client-side visualization platform for AR display on mobile devices. In this study, laser-scanned point clouds and their as-designed BIM models are stored in the server-side databases. The external analytic software, MATLAB, is used as the processing unit to develop the segmentation and estimation algorithms on the point clouds, as mentioned in the previous sub-section. Once the processing is done, further information such as discrepancies with their related positions on

the models/point clouds is annotated for further queries. As long as server-side processes have been finished, data can be downloaded to the client-side application through different IO functions. In this study, AR Inspector allows the as-designed model in FBX or IFC format to be imported into the client-side application. They are standard and compatible 3D and BIM file formats. As for the laser-scanned data, the application accepts an import through the PLY file format as the data with polygons. An Unity3D package called PCX library is used to support such data import function. Regarding the quality inspection information (discrepancy) generated through previous data processing, it can be queried through SQL once the client-side application needs to present it due to the requests by inspectors.

On the client-side application, three modules are implemented, including 1) Inspection Interpreter; 2) AR Display and 3) Inspector Guiding Interface. Inspection Interpreter module helps organize the annotated quality analysis results and presents them to the user systematically. AR Display module identifies the coordination system of as-designed models and establishes a discrepancy-embedded overlapping for the models to superimpose onto the real-world entities. About the Guiding Interface module, it is implemented for inspectors to check with the discrepancy results generated objectively by computers to conduct confirmation processes. The details on the three modules are shown as below:

Inspection Interpreter – This module is helpful for requesting annotated evaluation results from the database. It further converts all the discrepancy information into a generic representation. If an inspector raises an information query through Inspection Interpreter, such as showing the rebar spacing, the server-side database will provide necessary data as responses. In general, the positioning of components is treated as a Cartesian point (X, Y, Z). For distance measurement, it is described by two endpoints with a distance value. In this module, all the discrepancies that will be used for AR visualization are described as homogenous 4x4 matrix (translation X, Y, Z and rotation along X, Y, Z axes). They indicate the transformation needed in order to fix the current posture of the component to that of its as-designed one. For example, misplaced rebar can be fixed by going through a certain translation and rotation movements. These movements should be conducted based on the identified matrix.

AR Display Module – This module is developed to superimpose as-designed information onto the real formwork/rebar structure, further helping the AR-based inspection in the field. Such visualization provides an effective and intuitive method for inspectors to identify and confirm potential discrepancies. It just likes the virtual models actually exist in the real world. The virtual as-designed models are not always 100% matched with their as-built ones. It means that the relationship between the coordination system of virtual as-designed rebar/formwork and that of actual product contains potential deviation. Such deviation is considered in this module and the overlapped results of AR visualization show such deviation for inspectors to perform not only confirmation of the discrepancy reports generated by computers but also conducting their own judgments during the inspection.

Inspector Guiding Interface – The interface is designed for assisting the inspector to double-check the correctness of the computer-recognized discrepancies. It is useful for the inspector to deal with overwhelming dimensional information to avoid oversight or inaccurate judgments to be made. The discrepancies will be presented by the module one by one, for the inspectors to examine whether the issue really severe and necessary to be reported, or it just can be treated as error under tolerance and can be ignored. The discrepancy is shown with the fixing instructions. For example, misplaced rebar can be highlighted by the module and the inspectors need to drag it, on the touch screen of the mobile device, to its correct position where its as-design one located. Then the discrepancy is officially recorded in the final report. This is the main function that inspectors will utilize alongside with their own visual inspection and personal judgments.

5 VALIDATION

In order to validate the feasibility and usability of the proposed framework, a laboratory experiment was conducted. The proposed formwork dimensional quality assessment techniques were utilized in the experiment, including laser scanning data processing, AR display, and guiding interface. The details are shown below:

5.1 Test Specimen and Laser Scanning Results

One of the specific goals of this laboratory test was to estimate the two key dimensions of the formwork and rebar using laser scanning. Note that the estimation values will be fed to the AR Inspector for fabricators to facilitate their inspection using a tablet display. The test specimen with dimensions of

1500 mm (length) \times 1000 mm (width) \times 200 mm (height) was made of layered plywood and has 18 mm thickness. Two (top and bottom) rebar layers were installed in the wood formwork, and the diameters of the top and bottom rebars are 12 mm and 16 mm, respectively. Also, each top and bottom layer consists of 6 longitudinal and 9 transverse rebars. In addition, C-shape rebars were used to connect the top and bottom rebar layers. In the experiment, a phase-shift laser scanner, FARO M70, having a ranging error of 3 mm at 20 m was used. Figure 3 shows the specimen and the estimation results of the bottom and top rebar layers.

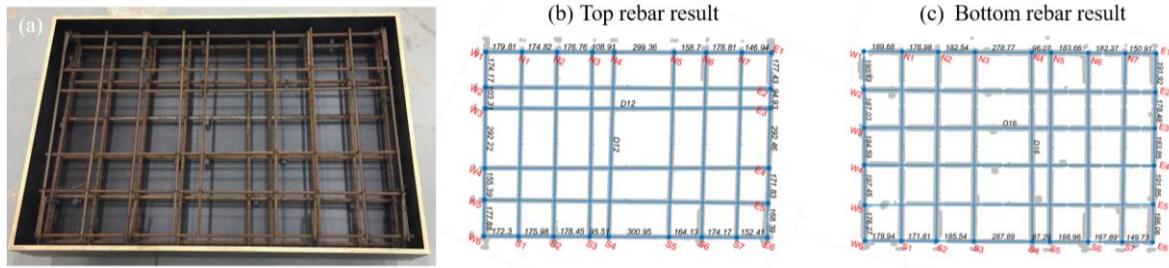


Figure 3. The specimen: (a) Overview; (b) estimation results of top rebar layer and (c) estimation results of bottom rebar layer

The dimension of two rebar checklists, including rebar spacing and concrete cover, were estimated by the proposed recognition steps described in Section 4.1. Note that N, E, S and W notations refer to the directions of North, East, South, and West, respectively, and the value shown between two rebar intersection points refers to the rebar spacing in mm. In addition, D16 and D12 shown in the middle stand for the rebar diameters of 16 mm and 12 mm, respectively. Table 3 shows rebar spacing and cover estimation results under the laser scanner's angular resolution of 0.036. By comparison with the actual measurement by measurement tape, the overall estimation accuracy of rebar spacing and the concrete cover was 1.72 mm, indicating the applicability of the laser scanning approach for the formwork and rebar inspection.

5.2 AR-based Inspection Results

The settings for generating AR visualization is shown in Figure 4(a). To accurately superimpose the virtual model of the specimen, a paper-based tracking target (with a unique textured pattern on it) was put on top and in the middle of the real specimen. It is supported by two aluminum rods hanging on two end-side of the formwork. Figure 4(b) shows the results of the AR visualization by using a tablet during the experiment.

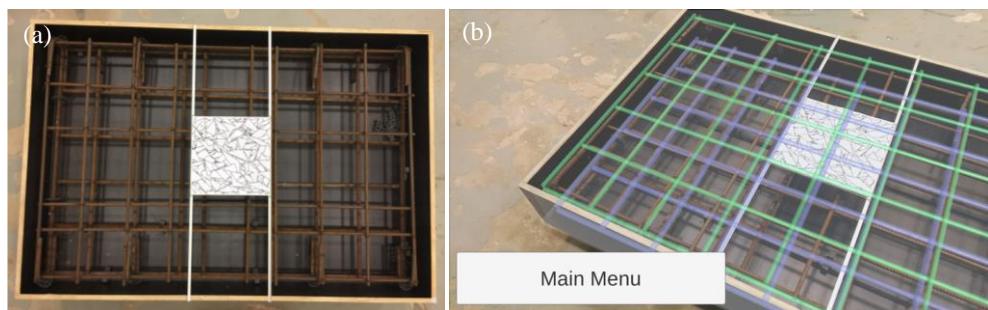


Figure 4. AR-based inspection process: (a) The tracking target; and (b) AR display

In this experiment, the Implemented AR Inspector prototype provides three basic functions for operations: 1) discrepancy report briefing; 2) manual inspection mode; and 3) discrepancy confirmation assistant. The discrepancy report briefing function is used off-line, showing the virtual models and discrepancy information on the screen of the tablet only. It is useful for the inspector to get an

understanding of the application and preview the evaluation results automatically generated by computers. As for manual inspection mode, it is an attempt to identify where the tracking target and estimate its postures in order to put the virtual as-designed specimen on the real one. It requires the inspector present aside from the specimen and manual quality evaluation judged by the inspector is possible. Figure 4(b) shows such a visualization. The virtual rebars in the top layers are colored as green, those in the bottom layers are in blue, and the formwork in transparent white, respectively.

The discrepancy confirmation assistant is implemented to show the content of the discrepancy report. The report is generated through the comparisons between the extracted dimensional information of laser-scanned data and that from its corresponding as-designed model. In this experiment, three rebars in the specimen are designed to be placed in the wrong positions. As shown in Figure 5, the discrepancy confirmation assistant shows the discrepancies in order for the inspector's reference. Corresponding instructions to fix the displacement are also provided in text or through AR display. In the case shown in Figure 5, the fixing instruction is shown: one transversal rebar (TT3) in the top layer (in red) is misplaced. The way to fix it is to follow the provided instruction "Please move TT3 misplaced rebar with red color to correct position with green color by 100mm." The arrows from the red bar to green one indicate the fixing direction. As long as the inspector acknowledges the discrepancy, all he/she needs to do is to drag the bar in red, along with the arrow direction and release it in the place where the bar in green located. Then the discrepancy will be officially issued in the final confirmed discrepancy report. Such a report contains the inspection outcomes and needs to be addressed through further manufacturing processes. Alternatively, the inspector can reject the discrepancy record generated by computers by simply clicking on the "That's OK, Next!" button. The discrepancy record will be discarded, judged by inspector's own professional experience. At the end of the experiment, all three discrepancies have been identified successfully at the data processing stage. And the related transformation matrices regarding the rebar fixing are also determined. They have been displayed to the inspector for further decision making. These show the feasibility of the proposed AR-based dimensional inspection approach.



Figure 5. The inspector guiding interface showing a discrepancy of a top transversal rebar

6 CONCLUSION

In this study, the research teams propose a systematic framework for formwork quality inspection in order to identify the requirements of performing formwork/rebar fixing tasks. A mobile application with developed data processing techniques on laser-scanned data, named AR Inspector, is implemented based on the proposed framework. Related experiment at the laboratory level is conducted to validate its feasibility. The results of the experiment show that the dimensional information of the selected specimen can be accurately extracted through dimension estimation processes and is capable to be used for compliance of the formwork and rebar design. The contributions of the study are thus drawn, on the design and implementation of intuitive and accurate quality inspection procedures as well as assisting aids by integrating laser scanning information and AR display. The visualization and automated dimension estimation processes help inspectors to identify discrepancies accurately after the manufacturing stage of the formwork and rebar arrangement. More importantly, the facilitation on the quality inspection is that the quality evaluation results generated by computers are confirmable judging

by inspectors' own professional experience and personal inspection results. Such a personal inspection process can be also benefited from the AR display as long as the quality of the positioning approach is reliable. The limitations of the current study include: the AR tracking target is still needed in the experiment, more advance positioning approaches, such as SLAM-based AR can be adopted for an improvement. The shapes of the formwork design capable to be extracted in this study are regular rectangle based on the developed data processing algorithms. Further improvements are expected in the future: wearable devices, such as Mixed Reality glasses, can be integrated to help inspectors get more intuitive experience. The connection with BIM standards regarding the data exchanging of the discrepancy information can be further established. It is expected that the field tests in terms of the productivity of such a proposed inspection approach can be carried out to validate its merit in practice.

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A Study on Multilayer Sub-contracting in Construction Industry of Hong Kong

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Abstract: Multilayer sub-contracting is a significant practice among the world, including Hong Kong. When a principal contractor secured a project from a developer, the specific jobs will usually be breaking down and sub-contractors with the lowest bid [1]. The adoption of multilayer sub-contracting has been a controversy issue which is considered as a two-side blade. While certain studies have been carried out to examine both the contributions, damages and improvements for multi-layer subcontracting, the construction industry and researchers are still waiting for a solid measure to enhance the system. Hence, this research attempts to study the advantages, disadvantages, conducts a comparison between single and multilayer sub-contracting and measures of current Hong Kong construction industry based on literature review, questionnaire and in-depth interviews. To achieve the objectives, Analytic Hierarchy Process (AHP) and total weighted score methods are adopted to examine and rank the criterion. The findings of this study provide a good basis for understanding the major reasons and problems caused by the adoption of multilayer sub-contracting. Besides, the identified safety perspective explores a new perspective regarding to issues of multi-layer subcontracting, which will serve as a solid foundation for further research to enhance safety performance. Finally, the findings of measurements towards improvement of multilayer sub-contracting will also provide a solid solution for construction industry.

Key words: multilayer sub-contracting, advantages and disadvantages, safety, measures, construction industry

1. INTRODUCTION

Subcontracting was described as “an organization which passes the provision of a service or execution of a task previously undertaken in-house to a third party to perform on its behalf” [2]. The history of subcontracting in Hong Kong can date after 1945, the end of the World War II and before the establishment of the government of Peoples Republic of China. At that time, Shanghai of China was one of the most modern cities in the world with advanced building technology. After the WWII, many construction firms from Shanghai came to Hong Kong together with their skills, technology and specialist knowledge [3]. Paul Y. Engineering is one of the examples. The number of “establishments” functioning in Hong Kong construction industry was 19,057 in 2006 whilst the number of persons

directly engaged was 135,337. Each of the establishments only employs 7 employees on average. Of these, 259 establishments are classified as main contractors, and 23,341 persons are directly engaged. Each of the main contractors employs 90 employees on average [4]. The report of the Census and Statistics Department of Hong Kong showed that the total number of “establishments” functioning in Hong Kong construction industry is 11,584 at that time. 430 are classified as main contractors, each of these employed 77 persons on average. The remaining are mainly subcontractors and specialist direct contractors. 9 persons were employed by each firm on average. Integrating the report on 2006 and data of 1987, the industry is growing whilst the size of the contracting firms is decreasing, indicating the ascension of using subcontracting [5].

Efficient, risk transferal, flexible and cost reduction were identified as the major reasons for adopting the subcontracting system in Hong Kong construction industry [6][7]. However, subcontracting is also deemed as a two-sided blade which problems including fragmentation, competitive bidding and non-value-added subcontracting layer arise [8][9]. Hence, a few researches have been conducted to improve the existing subcontracting system since it is considerably essential for the construction activities. Adopting a ‘Partnering’ between main contractor and subcontractor, limit the layers of subcontractors, change the practice of the lowest bid and implement a mandatory registration scheme were major recommendations suggested [10][11][12]. Yet, the effectiveness of these measures may require further observe..

2. RESEARCH METHODOLOGY

AHP is established for dealing with complex decision making, an effective aid to make the best decision. An AHP-design based questionnaire were distributed to the parties working in the construction industry [13]. A point scale was adopted to indicate the level of importance of each criterion as shown as Table 1. Decision hierarchy were developed for defining criterion of the advantage, problem risk factors correlated to safety impact correspondingly as shown in Figures 1 to 3. For those factors, they were extracted from previous research through literature review. Through the weighting by the respondents, calculations were carried out for data analysis process and the criterion would be ranked accordingly to their importance in either AHP method or total weighted score method. By using AHP method, the consistency ratio (CR) shall not exceed 0.1 for ensuring the validity of the results. Apart from conducting questionnaire survey, in-depth interviews were conducted to collect structural views on multi-layer subcontracting based on personal experience since we considered not only the solutions theoretically but also practical ways.

Table 1. Explanation of intensities (Scale) of AHP model [14]

Intensity	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2,4,6,8 can be used to express intermediate values		

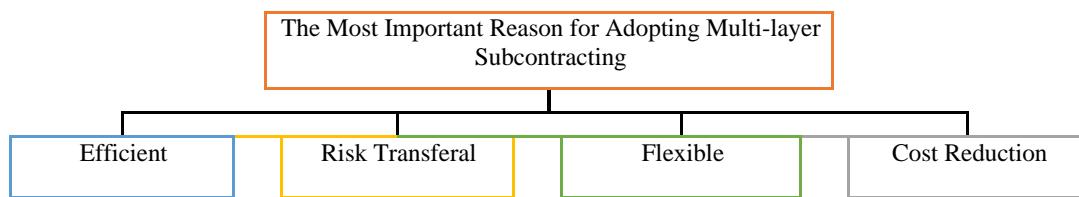


Figure 1. The decision hierarchy for selecting the most important advantage of adopting multi-layer subcontracting system

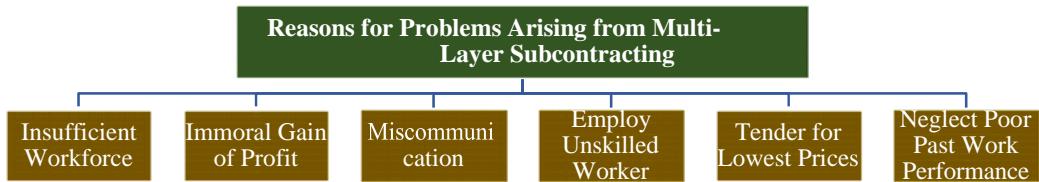


Figure 2. Hierarchy of the reasons for problems arising from multi-layer subcontracting

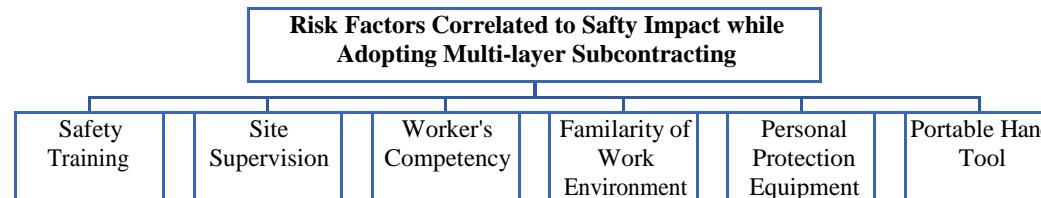


Figure 3. Hierarchy of risk factors correlated to safety impact of adopting multi-layer sub-contracting system

3. FINDINGS AND DISCUSSION

For THE questionnaire survey, 75% (30) responding rate was achieved. Among the respondents, more than a half of them had been working in the construction industry for 11 to 20 years. The respondents had diverse occupations listed varying from civil engineer, project coordinator, project manager, quantity surveyor and such alike. For in-depth interview, 8 out of 15 invitations had accepted. Different parties who had served the construction industry for 5 to 30 years from several institutions including developer, consultant, main contractor and subcontractor had responded to provide further discussions.

3.1 Advantages

A valid result (0.012, which <0.1) was generated through AHP calculation. Table 2 showed a detailed matrix responding to the importance of each advantages through comparison from questionnaire. Referring to Table 3, efficient (35.4%) was revealed as the most important reason for the adoption of multi-layer subcontracting system. In Hong Kong, the uplift demand of construction works becomes the rationale behind this finding, which more interpretations were provided by the respondents of interview. For developers, using multi-layer subcontracting system helps to reduce overhead and simplify the structure. In another mean, the developers are eligible to make optimize use of their resources in appropriate ways to enhance their performance. For subcontractors, the effect of specialization enables them to stay focus on their own trades to shorten the time of site operation. Besides, risk transferal (30.9%) was indicated as the second important criteria for adopting multi-layer subcontracting. A tight difference (4.5%) was recorded between the first and the second criteria, which might consider these two criteria were relatively important to each other. One of the respondents indicated that subletting 80% of works to subcontractors, or even 95% are usual practice in Hong Kong. The higher portion of sublet works, the less risks such as financial risks, project risks to bear.

Moreover, flexible (13.5%) was indicated as the least important criteria. One of the respondents of interview mentioned that subcontracting can help to reduce resources input for construction. Supplemented with the current situation in Hong Kong, the developers, main contractors and subcontractors are cash-rich to further expand their business in different area. Therefore, the low rank of flexible could be interpreted since the construction parties are less aware since they have subsidiary or partnering company to manage inputs.

Table 2. Matrix of the criterion of advantages for adopting multi-layer subcontracting

	Efficient	Risk Transferal	Flexible	Cost Reduction
Efficient	1	1.20	2.82	1.60
Risk Transferal	0.83	1	2.75	1.33
Flexible	0.36	0.36	1	0.86
Cost Reduction	0.62	0.75	1.17	1

Table 3. Consolidated priorities of the criterion

Category	Priority	Rank
Efficient	35.4%	1
Risk Transferal	30.9%	2
Flexible	13.5%	4
Cost Reduction	20.1%	3

Table 4. Matrix of the criterion of problems encounter from multi-layer subcontracting

	Insufficient Workforce	Immoral Gain of Profit	Mis-communication	Employ Unskilled Worker	Tender for Lowest Prices	Neglect Poor Past Work Performance
Insufficient Workforce	1	1.3237	2.6467	1.2673	1.4647	2.2067
Immoral Gain of Profit	0.7555	1	3.5388	2.8213	2.5179	4.3844
Miscommunication	0.3778	0.2826	1	2.6215	1.7473	2.8929
Employ Unskilled Worker	0.7891	0.3544	0.3715	1	1.6473	3.8254
Tender for Lowest Prices	0.6827	0.3972	0.5723	0.6071	1	3.9205
Neglect Poor Past Work Performance	0.4532	0.2281	0.3457	0.2614	0.2551	1
Total	4.0583	3.586	8.475	8.5786	8.6323	18.2299

Table 5. Normalized principle eigenvector

	Normalized Principle Eigenvector	Rank
Insufficient Workforce	22.77%	2
Immoral Gain of Profit	29.06%	1
Miscommunication	15.94%	3
Employ Unskilled Worker	14.24%	4
Tender for Lowest Prices	12.47%	5
Neglect Poor Past Work Performance	5.22%	6

3.2 Disadvantages

Based on the data, the consistency ratio is 8.72% that considered as consistent. According to the result, the most important criteria and the second important criteria of problems encounter from multi-layer subcontracting system are immoral gain of profit (29.06%) and insufficient workforce (22.77%) respectively, two of them counted over 50% that indicate most of the respondents believed it is common in building and construction industry. Half of the interviewee reflected that over subletting the contract to another lower-tier subcontractor to earn the profit damage the subcontracting system, unrealistic price can't finance the task; also, aging problem is also a main reason that arising insufficient workforce. For the least important criteria for multi-layer subcontracting system is neglect poor past work performance (5.22%), one of a interviewee mentioned that construction project is unique, not identical and repetitive, past performance only can be reference to be considered that can't induce in new project under different conditions.

3.3 Safety Issue

To compare the relative importance of six risk factors correlated to safety impact while adopting

multi-layer subcontracting. The risk factors are listed IN Table 6 and findings are summarized in Figures 4 & 5.

Table 6. Risk Factors

Risk Factor	Definition of Risk Factor
Safety Training	Insufficient resource for safety training
Site Supervision	Insufficient qualified site supervision personnel
Workers' Competency	Hiring of non-skilled worker
Familiarity of work environment	Unfamiliar of works environment due to frequent change of work location
Personal Protection Equipment	Insufficient provision of PPE
Portable Hand Tool	Poor quality of portable hand tool as lack of maintenance

Aggregation of judgments for 30 Participant(s)

	1	2	3	4	5	6
1	1	1.27	1.18	1.68	1.47	2.05
2	0.79	1	1.51	2.12	1.66	2.78
3	0.85	0.66	1	2.02	1.62	2.34
4	0.60	0.47	0.49	1	0.62	1.13
5	0.68	0.60	0.62	1.61	1	1.61
6	0.49	0.36	0.43	0.89	0.62	1

Figure 4. Matrix of the criterion of risk factor correlated to safety impact for adopting multi-layer subcontracting system

Consolidated Priorities

Consistency Ratio CR: 0.8%

Category	Priority	Rank
1 SAFETY TRAINING	22.1%	2
2 SITE SUPERVISION	23.7%	1
3 WORKERS COMPETENCY	20.0%	3
4 FAMILIARITY OF WORK ENVIRONMENT	10.6%	5
5 PERSONAL PROTECTION EQUIPMENT	14.5%	4
6 PORTABLE HAND TOOL	9.2%	6

Figure 5. Ranking table of risk factor

For confirming the validity of our survey result, consistency check was done. The consistency ratio of our survey result was 0.008 (< 0.1), i.e. the result is valid. Based on the survey result, site supervision and safety training are the top 2 risk factors contributed to safety impact while adopting multiplayer subcontracting. Besides, these 2 risk factors added up was 45.8%, it almost occupied half of the total. It revealed that lower-tier subcontractor was lack of qualified site supervision personnel and gave insufficient resource on safety training for cost saving reason. On the other hand, the above 6 risk factors could be divided into 3 categories as site management, labor and equipment shown in Table 7. Site management is the most critical factor related to the safety impact while adopting multi-layer subcontracting system.

Table 7. Ranking of category group

Categories	Criterion	Weights	Rank
Site Management	Safety Training, Site Supervision	22.1% + 23.7% = 45.8%	1
Labor	Workers' Competency, Familiarity of Work Environment	20% + 10.6% = 30.6%	2
Equipment	Personal Protection Equipment, Portable Hand Tool	14.5% + 9.2% = 23.7%	3

4. PROPOSED SOLUTION

In this study, four proposed measures were introduced to interviewees. The method includes:

- (a) Adopt a ‘Partnering’ Between Main Contractor and Subcontractor
- (b) Limit the layers of subcontractors
- (c) Change the current Tender practice
- (d) Implement a mandatory registration scheme

The findings from the survey have been summarized in Table 13. The total weight score method is obtained. The rank of relative effectiveness between these measures can be obtained according to their total weighted scores.

Table 8. Scores of the Proposed Solutions

Method	Effectiveness of methods					Total weighted scores
	1	2	3	4	5	
Adopt Partnership	1	9	9	10	1	90
Limit Layers	0	1	4	17	8	122
Change Tender Practices	0	1	8	13	8	118
Implement mandatory registration scheme	0	5	8	15	2	104

- (a) Adopt a ‘Partnering’ Between Main Contractor and Subcontractor

The definition of partnering for this research is a simple term to a non-legally relationship between contracting parties in the industry in order to achieve a set of common goals in addition to individual goals. As per the Figure 11, “Adopt a ‘Partnering’ Between Main Contractor and Subcontractor” is considered as the most ineffective methods. Also, all the interviewees did not prefer adopting a “partnering” relationship between MC and subcontractor. It is difficult to set a mutual goal and it is not easy to trust each other. Also, the use of contractual terms in subcontract is always unfair to subcontractor. Therefore, it is hard to build up a fair and trustable relationship.

- (b) Limit the layers of subcontractors

It is believed to be the most effective methods as per Figure 11. The appropriate level subcontracting was also indicated in the interview section. It is recommended to prohibit the first-tier subcontractor to sublet more than two layers and included this as a Special Conditions of contract. Reducing the layers can help coordinate contractors more effectively. When problems occurred during the project, it will be easier to identify and quicker to resolve the problem. Moreover, less layers which also means better chance the bottom layer subcontractors will have a more reasonable profit margin.

- (c) Change the current Tender practice

It is one of the effective methods from the questionnaire result. The current tender practice should be reviewed to alter the atmosphere from cost-drive to value construction. A type of score system mechanism that evaluates not only the price but also their past performance. The sub-contractors should submit proven performance record including works quality, safety records, wages payment records etc., for reviewing their capacity. In the current practice, the main contractor usually awards the subcontract to the lowest bidder to maximize its profit. All interviewees agreed that the current tender practice of subcontracting system has its disadvantage and there are barriers to change the practice. It is recommended that the developer should step forward to change the situation and provide incentive to both main contractor and subcontractors.

- (d) Implement a mandatory registration scheme

In the current stage, it is not necessary to implement a mandatory registration scheme according to the questionnaire result and interview. The government should review their current registered contractor scheme and consider extending the registration scheme to other types of contractors. Also, the scale of registration has to be deeper into the site workers, not only the companies. Also, the main contractor/ upper tier subcontractor in private sector should gradually introduce contractual conditions controlling the employment of Registered Subcontractors.

5. CONCLUSION

Considering the advantages of adopting multi-layer subcontracting, an upward trend of adopting multi-subcontracting system has been observed from the construction activities in Hong Kong, whereas the adoption has changed. From the previous findings, cost reduction was the most important reason for using multilayer subcontracting system. However, efficient replaces as we can observe from this finding. An inter-relationship can also be interpreted among the four advantages related to the use of multilayer sub-contracting. Besides, the research result of problems of subcontracting is similar to previous research findings, the immoral gain of profit rank as the top that indicate the subcontractor still act like a broker to sublet the contract to lower-tier subcontractor to earn the profit is very common. The research result has also clearly said that the situation has not get any change in this two decades. But just a like surprise that insufficient workforce is the 2nd important criteria that point out that the aging problem of building and construction industry become more serious since the past ten years, that's why you can hear about import labour to replace the vacancies. Effectively measures focus on tackling these two criteria can minimize nearly 50% problem arising from multilayer sub-contracting. Site management is the most critical factor related to the safety impact while adopting multilayer sub-contracting work and therefore, it is recommended the industry should put more focus on enhancing management skills in the scope to provide more safety trainings and supervision in order to minimize work injury and diffuse a safety awareness culture from main contractor to the bottom layer. Also, further research about site management in multilayer sub-contracting system is suggested.

To conclude, subcontracting is an influential strategy for the accomplishment of construction contracts. If properly managed by contractors, it will facilitate the execution of works in a cost-effective manner and allocate resources efficiently. However, without appropriate management, uncontrolled subcontracting could have adverse impact on the progress and quality of works. In order to strengthen the effectiveness of the practice, it is suggested that the current tender practice should be reviewed to alter the atmosphere from cost-drive to value construction. Also, prohibit the first-tier subcontractor to sublet more than two layers is recommended that help coordinate sub-contractors more effectively.

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Analysis and survey of design decision making process in steel production process

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Abstract:

In the building construction, the steel-frame work occupies an important position in terms of structure, cost and quality.

Especially in Japan, steel frames have traditionally been the main structure of many buildings.

For steel-frame works in such positions, this paper investigates an existing steel fabricator to clarify the actual conditions of design decision making process and management method in steel production process.

This study focuses on a steel fabricator (Company M in the following sentences), whose main market is Japan and which has facilities in Thailand, China, and Japan. Company M uses QR codes to control the production status of products, and exchanges all information between inside and outside the company via specialized departments in the form of documents.

The authors have already analyzed the relationship between production lead time and defect rate based on actual project data at Architectural Institute of Japan in 2016. In 2019, we expressed the process from the confirmation of the design information of the current steel frame to the production by WBS, and clarified the relationship between the production lead time and steel frame product quality structurally. In this paper, the authors report the progress of the survey conducted so far, the positioning of the collected data, and the future survey policy.

Key words: Steel member fabrication, Production management system, production period, Work Breakdown Structure

1. Introduction

Since Japan is an earthquake-prone region, excellent earthquake resistance is required for building structures. In Japan, where the land is small and the population and industry are concentrated in big cities, large-scale facilities are often considered to be high-rise or super-high-rise buildings, but structural designers and major building constructors have established super-high-rise earthquake-proof technology using steel structures, and major steel manufacturers have responded to such demand by supplying a large amount of building steel.

On the other hand, stringent requirements for seismic performance require complex beam-column jointing methods and seismic and seismic isolation components, making it difficult to standardize the

cross-section of components. In addition, as building functions have become more sophisticated and various industrialization methods have been adopted, building steel frames have complicated details with various attachments.

However, many of these complex details are determined after the construction project has entered the construction stage through coordination among multiple specialized works. Another problem is that the scope of responsibility for design and construction is ambiguous because general contractors in Japan are involved in a wide range of businesses.

In the production of building steel frames, specifications, materials, shapes, processing methods, inspection methods, etc. of products are examined in various stages from design to construction (steel fabrication). Though it is desirable that these decisions are made early in the design stage of the upstream process, in reality, the details are often decided after the examination of the construction plan and the selection of the specialized contractor as described above.

The reasons for this are as follows.

- ① Detailed field surveys and construction studies on the ground and the condition of the access roads to construction site may reveal this.
- ② Different projects have different steel details (especially a joint)
- ③ Know-How/Capacity and characteristics of machine tools are different for each fabricators which is responsible for steel frame production.
- ④ Specialized contractors vary in specifications for equipment, interior and exterior fittings, etc.
- ⑤ Ancillary hardware (secondary hardware) includes temporary hardware such as scaffolding and fall prevention, crane frame, etc., and many parts which are decided in detail at the construction planning stage.

Essentially, specialized contractors make estimates and contracts based on the specifications shown in the design documents, and perform their work. If details are not decided at the time of contract, the risk of fluctuation of construction period and price increases. In addition, if the decision is sent later and the steel fabrication period is oppressed, the adverse effect on the product quality may occur.

However, there are no clear indicators as to what should be prioritized among the various decisions related to steel frame production, what should be decided by what time, and the extent of the impact on cost, construction period, and quality if the decision is delayed.

The purpose of this study is to establish and verify the effectiveness of the mechanism to rationally judge how much lead time is required for each process of the building steel frame production work, especially from the decision making to the completion of execution, how the process is delayed (Changes in the critical path) and how the process affects the process to the steel frame erection.

In this study, the detailed work process from the design of steel frame construction to the completion of site erection is analyzed based on the investigation of the actual project, and it is shown in the WBS and network process chart, and the relation between each work and the person in charge is specified.

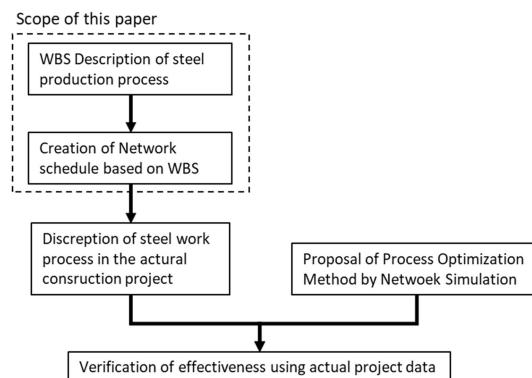


Figure 1. overall research framework

The procedure is as above (Figure 1):

- ① WBS (Work Breakdown Structure) description of steel production process
- ② Creating a WBS-Based Network Roadmap
- ③ Describe the actual project process using the network roadmap
- ④ Proposal of optimization method of production process by simulation

⑤ Verification of effectiveness using actual project data

This report describes the progress of the survey conducted so far, the positioning of the collected data, and the future survey policy.

2. Achievements to date

2.1. Analysis of the Production Period and the Number of Defects

Focusing on the relationship between steel frame fabrication period and product quality, the authors investigated the in-house data of steel frame fab, and analyzed the correlation between the fabrication period (Number of days from the date of establishment of design information to product inspection) and the number of defects (Number of defects in internal inspection records) [7]. However, a negative correlation was expected in which the number of defects decreased as the production period lengthened, but a clear conclusion was not obtained. (Figure 2)

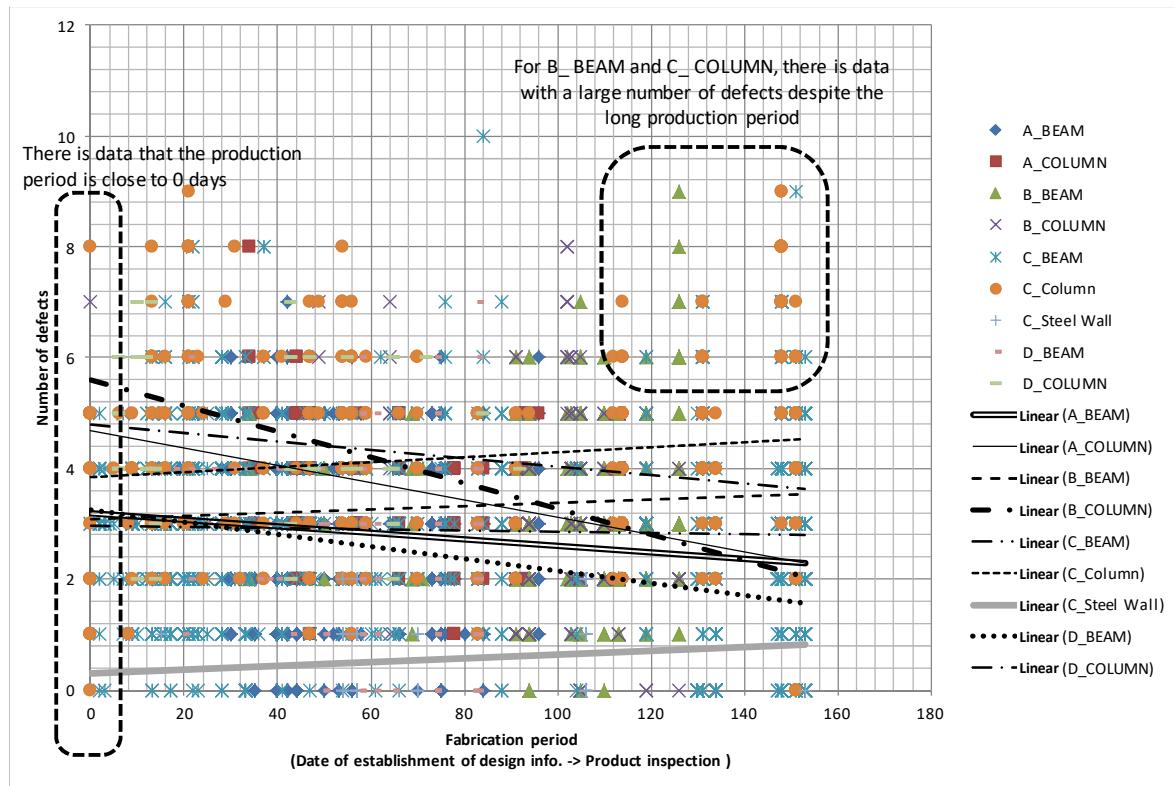


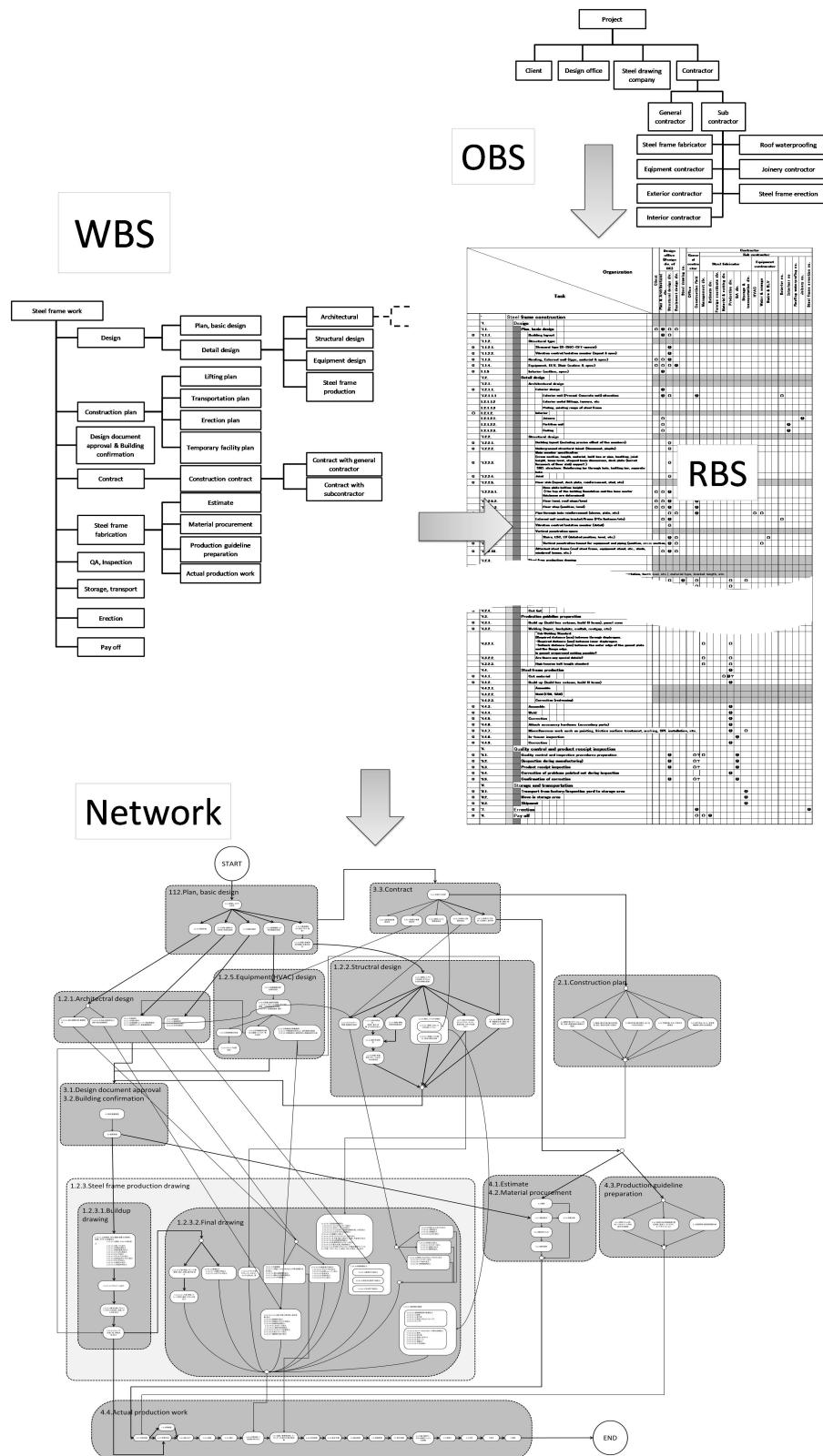
Figure 2. Relationship between production period and number of defects

In this analysis, the number of days from the drawing approval date (the date of change, if there is any change) to the date of product inspection was taken as the production period, and the number of defects in in-house inspection was considered as a measure of quality. However, in actual building steel frame production, there are some matters such as the size and material of main materials decided in the early stage of steel frame design and others such as ancillary hardware decided in the later stage. In addition, there are various defects of products with different seriousness (Impact on cost, construction period and quality).

2.2. WBS, OBS, and Business Flow

Next, in order to grasp the whole image of steel frame production work, the authors listed the whole process of steel frame production referring to the project planning method proposed by P. Morris (Project Planning Process) [8], and tried to identify the person and organization to carry out the processes and to analyze the context between the processes [10] (Figure 3).

Figure 3. Relationship among WBS, OBS, and RBS in the project planning method



In this report, each process of steel frame production was described in WBS (Work Breakdown Structure), persons and organizations involved in steel frame production were described in OBS (Organization Breakdown Structure), and which person and organization shouldered which process was summarized in RBS (Responsibility Breakdown Structure) (Table 1).

Table 1. RBS (Responsibility Breakdown Structure, partial)

It is the company that makes the detailed steel drawing, but in fact, it may be a department of the fab or directly employed by the general contractor. The detailed steel structure drawing is based on the results of structural design, but at the same time, information on facilities, stairs, EVs, PC exterior walls, fittings, etc. provided by specialized contractors is necessary. Similarly, construction plans of general contractors for temporary construction, lifting and erection are reflected in steel frame drawings.

Furthermore, the context of each process is summarized in a work flow diagram. Design information of main materials (Material, section, length, fitting specifications, etc.) is mostly decided at the stage of detailed structural design, but among secondary hardware, specifications of equipment frame, mounting bracket for staircase and EV, PC fastener, reinforcing bracket for fitting, etc. are often different depending on specialized contractors, so details are often decided after selecting a specialized contractor.

2.2. Process simulation by network method

It is expressed in the form of the network schedule based on the description of steel frame production process using WBS.

In the example shown in Figure 4, there is a constraint in the context of each process of drawing, ordering materials, and manufacturing, but by advancing a part of the decision making, the start time of ordering and processing can be advanced and the work can be started in duplicate. In the process simulation of an actual project using a network technique, the process can be optimized by finding a process having a loose changeable constraint condition and changing the constraint condition.

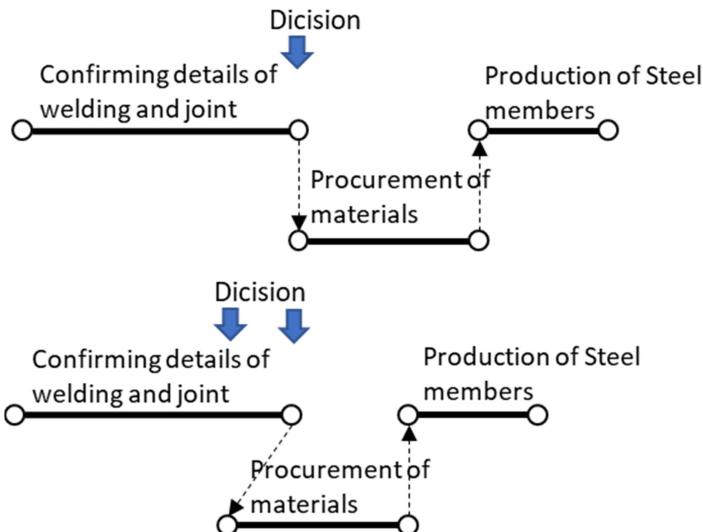


Figure 4. constraints between processes

3. Issues to be considered in the future

At present, authors collect and analyze the records of actual projects for the internal documents of the steel frame fab to which some authors belong (Table 2).

Table 2. documents under investigation

documents and data		information that can be obtained
① Schedule	① -1 Site Master Schedule	Initial draft of the overall project schedule
	① -2 Proposed process for FAB personnel	Although it is the material in the middle process, it is convenient to grasp the whole steel construction.
	① -3 Fab-Interior Production Schedule	Production schedule for each product
② Drawing	② -1 Construction Documents	design and specifications at the time of contract characteristics of steel frame
	② -2 APPROVAL DRAWINGS	Detailed view of steel frame, difference between contract and production Added Information
	② -3 Fab diagram	Production drawings, fittings, and details used in the factory are copied one by one from the list format.
③ Change	③ -1 Design Change / additional work order Record	Change due to owner or design office GC directed changes additional work due to fab reasons, such as error correction
④ quality control	④ -1 Defect Correction Records	Defects discovered through in-house inspections
⑤ Mail		Decision-Making process of design drawing ⇒ steel detail drawing history of change orders, additional work, and revisions
⑥ meeting minutes		Indications and instructions from GC and other SCs

The documents to be investigated include (1) Schedule charts, (2) drawings, (3) change records, (4) quality control records, (5) mail, and (6) meeting minutes. It is considered probable that these documents occurred at each stage of design, contract, detailed examination, drawing of steel frame, steel frame production, and product inspection (Figure 5).

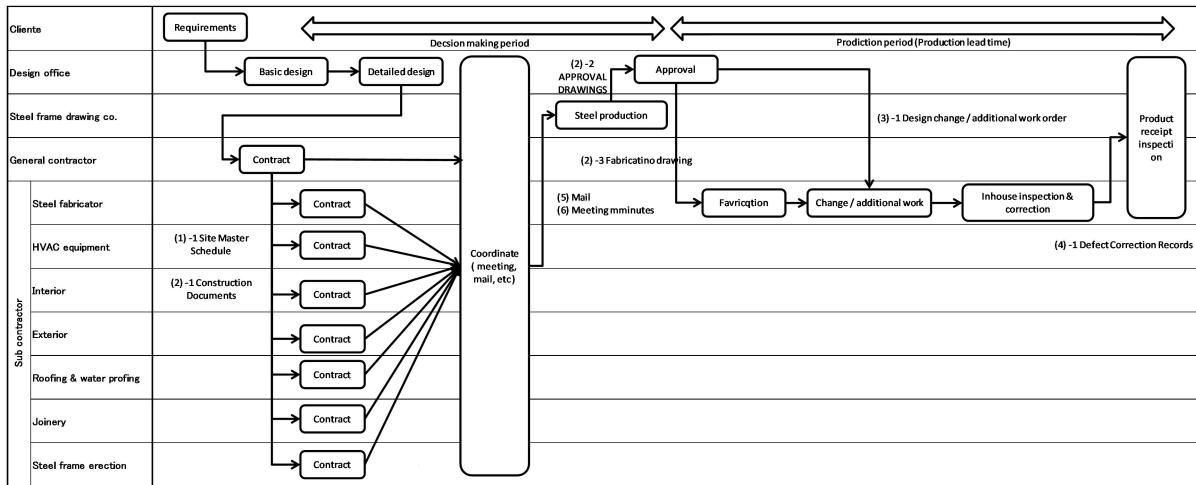


Figure 5. Document timing and role

For example, it is possible to know what kind of information is added at the construction stage by comparing a drawing ((2) -1) at the time of contract with an approval drawing ((2) -2). Also, by comparing the record of design change and additional work order ((3) -1) with ((1) -3) fab internal production schedule, it is possible to analyze how the delay of design information determination affected the production process.

In the future, the collection and analysis of the record of the actual project will be advanced, and the design decision making process in the steel frame production process will be clarified by the hearing to designers and general contractors.

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II. SCHEDULE AND COST MANAGEMENT (A2)

Challenges and suggestions of resource planning for standardized concurrent construction

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Abstract: Concurrent construction offers considerable improvement for shorten the project duration of its production process. Therefore, standardized concurrent construction is widely applied in building construction projects. However, resources planning for standardized concurrent construction project is manually developed by construction manager. This practice is not effective since it is time-consuming and error-prone for managers to identify all project-specific information, distinguish different activity-resource types, interpret these types and analyze how they affect resource allocated on an ad hoc basis. Therefore, this research investigates the opportunity for leveraging activity modeling to enable automated resource planning for standardized concurrent construction during project development, with identifying the characteristics of construction activities under standardized concurrent planning and determining the activity-resources types that affects resource planning. Both will function as a basis for modeling these construction activities in a computer-interpretable manner and for automation in resource planning.

Key words: Resource management; Standardized concurrent construction; Project planning;
Characteristic of construction activities; Activity-resource types

1. INTRODUCTION

Optimum resource planning is one of the key impact factors that affect the smooth production progressing of a construction project, which is more important to standardized concurrent construction (SCC) project that achieve the maximum duration overlapped in scheduling the construction activities [1-3]. SCC is designed to reduce the production time in a maximum level, in which a major set of activities is resulted in highly interdependent activities, i.e., at least two activity groups that depend upon each other to start and progress [3].

1.1 Resource planning for standardized concurrent construction project

Manual allocation is mainly applied in resource planning for construction projects [4]. This practice is not effective since it is time-consuming and error-prone for managers to manually identify all this information and make the allocation for all project-specific activities of concurrent construction [5]. In addition, inconsistent identification and input may result in discrepancies among different types of resources' planning, which affects the concurrent construction activities' progressing as some of them are interdependent with each other [1]. Therefore, there is a need of automation for supporting the resource planning in a quick and consistent manner, rather than such a manual manner. To enable

automated resource planning for SCC project, initial steps are 1) identifying the characteristics of construction activities of SCC projects; and 2) determining the activity-resource types of SCC activities. Both of them will function as a basis for research efforts related to capture reliable information in modeling these construction activities as a computer-interpretable manner and automation in resource planning.

1.2 Modeling construction resources in activity representation

The first step in automated resource planning is to formalize a generic activity modeling capturing resources information in a computer-interpretable way. The benefit of such an activity modeling, is that once the users represent the required resources within it, then the system can automatically generate the project-specific instances of those resources. The opportunity for leveraging activity modeling in resource management of SCC project development is that enabling automation in resource planning. Recent studies have clearly shown that even industry had applied SCC in building projects, tools such as Critical Path Method and Program Evaluation and Review Technique are not available for modeling concurrent activity groups that are interdependent [3, 6].

Activity representation provides the basis for an explicit modeling of construction knowledge to enable construction managers to develop the project plan in a fast and constant manner. Compared to conventional method, activity representation can enable the related resources be allocated and updated quickly even once change order is issued by the client. Available activity modeling that enable capturing and transferring construction information are mainly based on the OARPLAN and AROW schemas [7-11]. Construction activity representation in this area are extending from the tuple, i.e., <Action>, <Resources>, <Object>, and <WorkArea>, which is available for project prediction such as planning and scheduling, etc. [7, 12-15].

Even current activity representation has specified its specific actions and resources for construction planning and scheduling, it is limited to model how SCC activities are going to be executed with its related resources, i.e., which activity groups are interdependent and when to progress them; which objects will be progressed by different activity groups; and which activities require critical, named or designated resources. Those representations extended from OARPLAN have formalized resources as who and how to proceed the work, including manpower, equipment and material. However, this representation of resources does not accommodate the production details of construction activities, such as resource specific types, its available work hours and production rate. Generally, representation for SCC project is required to enable to retrieve the above activities, its groups' relationships and information, which is necessary for automated generation of resource planning.

In conclusion, current available knowledge is not available to fully capturing the necessary information of SCC projects for automated resource planning, in the following section of this paper, these will be discussed with a case example, and the opportunities with a specific emphasis on supporting SCC projects will be included.

2. MOTIVATING EXAMPLE

This section will illustrate the above knowledge gaps by using a case example. Figure 1 shows part of the plan of a SCC case. Taking rebar bending activity as an example, which belongs to main structure engineering, it has been represented using AROW schema as Figure 2 shows. However, such a representation cannot differentiate 1) whether the group the rebar bending activity belongs to are interdependent with other activity groups or not and when they have to start and progress; 2) whether the wall will be progressed by activities from other groups; whether it occupies the critical path with named or designated resources needed. In addition, this representation cannot accommodate the production details of resources such as the required available time and production rate, etc. All of these aspects is necessary to permit the automated resources planning for SCC projects.

As mentioned before, activity modeling is being proposed and applied for representing and storing construction information throughout the production process. This research will aim at automated resource planning for SCC in residential building projects. Therefore, the anticipated approach does not only make use of the activity modeling, but also leverages this medium for automated resource planning that predict and update the resource allocation effectively. In order to enable the automated resource planning, there is a need to capture concurrent construction information in a computer-interpretable format. Along with this research target, the next section will present the results of this study in which characteristics of SCC activities are investigated and activity-resource types are formalized, which is

the basis for developing the activity representation and for use in automated resource planning.

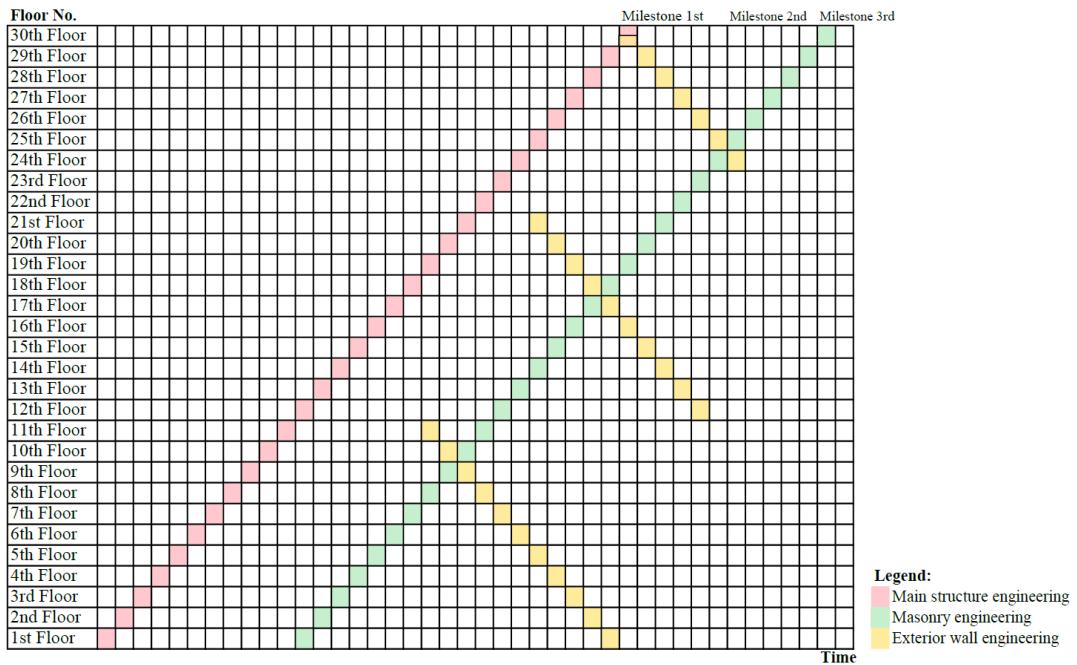


Figure 1. Part of a SCC project's plan

AROW Example		Activity		Rebar Bending
		Action	Bending	
Resource	Labour	Rebar Workers		
	Equipment	Bar Bending Machine		
	Material	Rebar		
Object		Wall		
Work area		Site Rebar Processing Area		

Figure 2. Activity example represented using AROW schema

3. DIFFERENT TYPES OF ACTIVITY-RESOURCE REQUIRED OF SCC PROJECTS

Activity-resource type, which affects the resource planning, is the basis to automated resource planning. This section describes the 192 types concerning activity-resource of SCC activities. Without automated resource planning for SCC projects, construction manager should manually distinguish different activity-resource types and interpret these types for resource planning, which is not efficient as the number of possible activity-resource types of a construction activity reaches about two hundred.

3.1. Characteristics of SCC activities

Regarding activity-resource, the characteristic of SCC activities serves as precursors of the resource-use type differentiator (RUTD). Therefore, six characteristics were identified based on observations, literature reviews, and case studies. These six characteristics indicates how RUTDs should be proceed concerning activity-resource of SCC activities (Figure 3). These six characteristics are:

C1: SCC activities are classified into six groups based on the overlapped progress, i.e., Main Structure, Masonry, Plastering, Exterior Wall, Dismantle Scaffold, Interior Decoration. This characteristic derives RUTD 1.

C2: Some SCC activity groups are interdependent, in which at least two groups depend on each other to start and progress [3]. This characteristic derives RUTD 2.

C3: Some object needs to be progressed by activities from different groups. This characteristic derives RUTD 3.

C4: Some SCC activity groups are partly or wholly occupying the critical path, while others do not. This characteristic derives RUTD 4.

C5: Some SCC activities require named resources, rather than resources that satisfied its requirements. This characteristic derives RUTD 5.

C6: Some SCC activities are required a designated resource, which is not allowed to use by other activities. This characteristic derives RUTD 6.

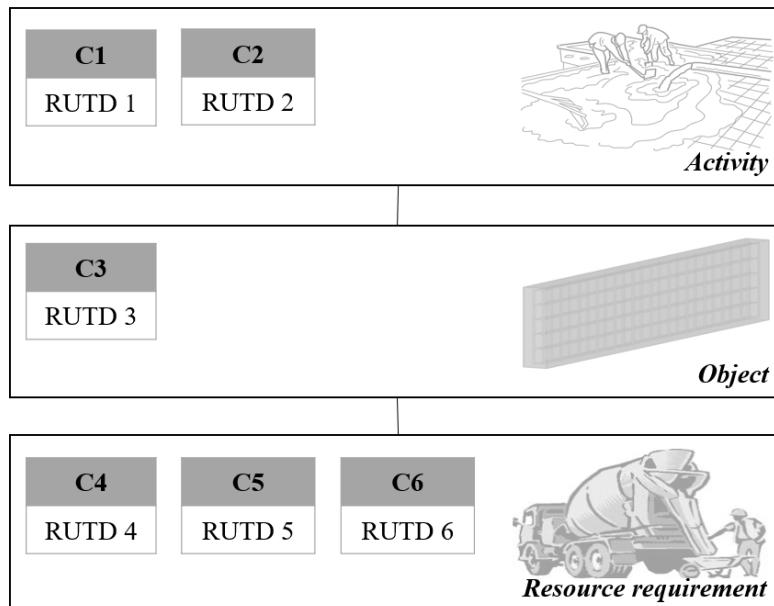


Figure 3. Derivation of RUTDs based on six characteristics

3.2. Activity-resource types

Resource-use type differentiators (RUTDs) are used to distinguish between different activity-resource types in automated resource planning of SCC projects. An activity-resource type of a SCC activity can be characterized as a combination of choices among these RUTDs, and automated resource planning checks the chosen group of RUTDs to proceed the resource allocation. Based on the six characteristics of construction activities, this research defined six RUTDs considering three perspectives (i.e., activity, object and resource). The differentiation of SCC activities was defined in terms of resource-use and its calculations as Figure 4 shows, which concerns all activity-resource types simultaneously. The six RUTDs are:

RUTD 1 differentiates between Main Structure, Masonry, Plastering, Exterior Wall, Dismantle Scaffold, and Interior Decoration activity groups.

RUTD 2 differentiates between interdependent and independent activity groups.

RUTD 3 differentiates between objects that need to be progressed by activities from different groups and those that only be progressed by activities from same groups.

RUTD 4 differentiates between resources that are critical and non-critical ones.

RUTD 5 differentiates between activities that required named resources and those required resources with certain features.

RUTD 6 differentiates between activities that required designated resources and those do not require designated resources.

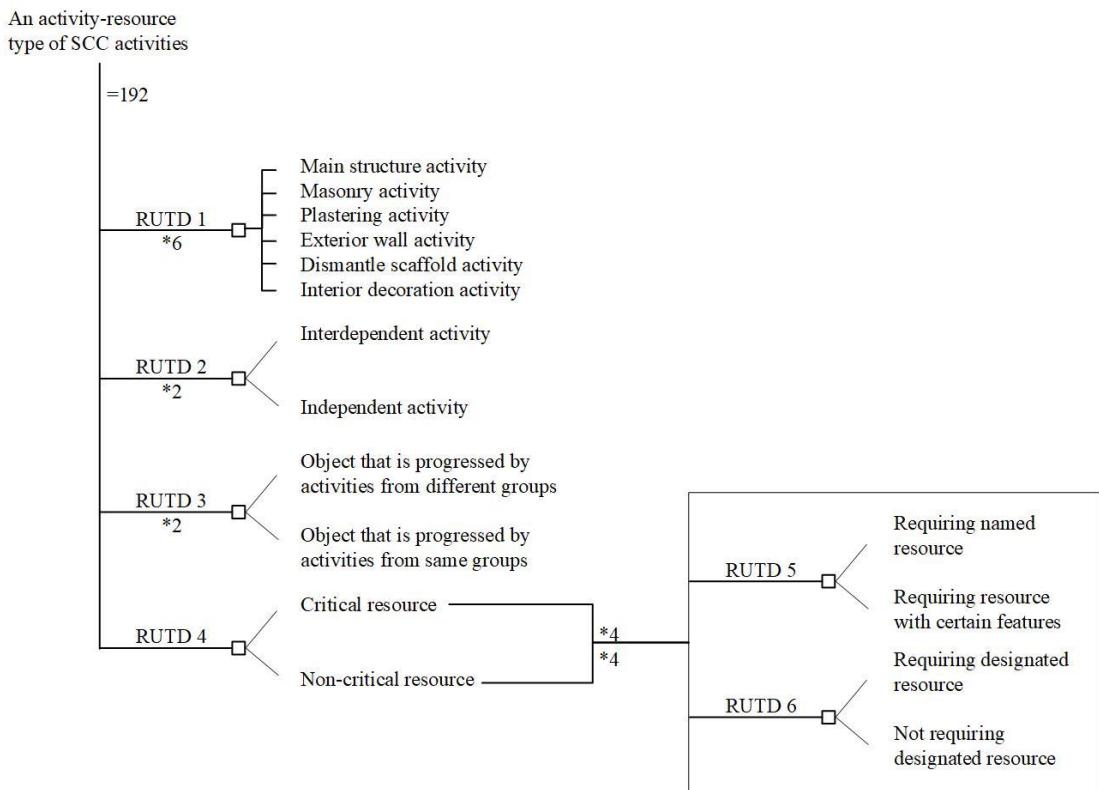


Figure 4. Differentiation of construction activities in terms of resource-use and its calculation.

4. CASE STUDY

In order to introduce possible benefits that can be gained by automated resource planning, this research conducted a case study. This case is a SCC residential project with 32 story high. Its typical floor was selected as a test-bed (Figure 5). This research investigated main structure activity group as listed under Table 1, presenting the information about 13 activity instances as an example. Afterwards, these activities were manually analyzed and mapped with specific resource instances in this study, which aimed to introduce the opportunities and benefits of automated resource planning for SCC projects.

4.1. Method

During this case study, this research investigated 13 activities within this typical floor example. Based on the project data, this research differentiated these activities based on their activity-resource types and analyzed how they types affect the resource allocated. The case study took two scenarios as a basis to further investigate how leveraging activity modeling to enable automated resource planning can help the construction manager during project development, where the current practice is not effective. In addition, this case study only focused on manpower resource variable to record and compare the changes between these two scenarios.

4.2. Results

As showed Table 1, these 13 activities are categorized into five types according to different combinations of choices among the formalized RUTDs. As all of these activities belongs to main structure activity group, their RUTD 1 are the same choices. In SCC planning, main structure, masonry and plastering activity groups are overlapped and interdependent by occupying part of the project critical path, therefore, the RUTD 2 of these activites are all chossing the interdependent one. In addition, as activities belonging to main structre activity group are scheduled in critical path, their RUTD 4 results are also same with each other. Consequently, what makes the activity-resource type different between

these 13 activities should be their choices about RUTD 3, 5, 6. Usually the construction manager needs to distinguish these activity-resource types and interpret them before resource planning as the amount allocated will be affected. For example, the resource amount allocated to these 13 activities will be affected by the scheduled length of the overall critical path of this SCC project, which are detailedly discussed as follows.

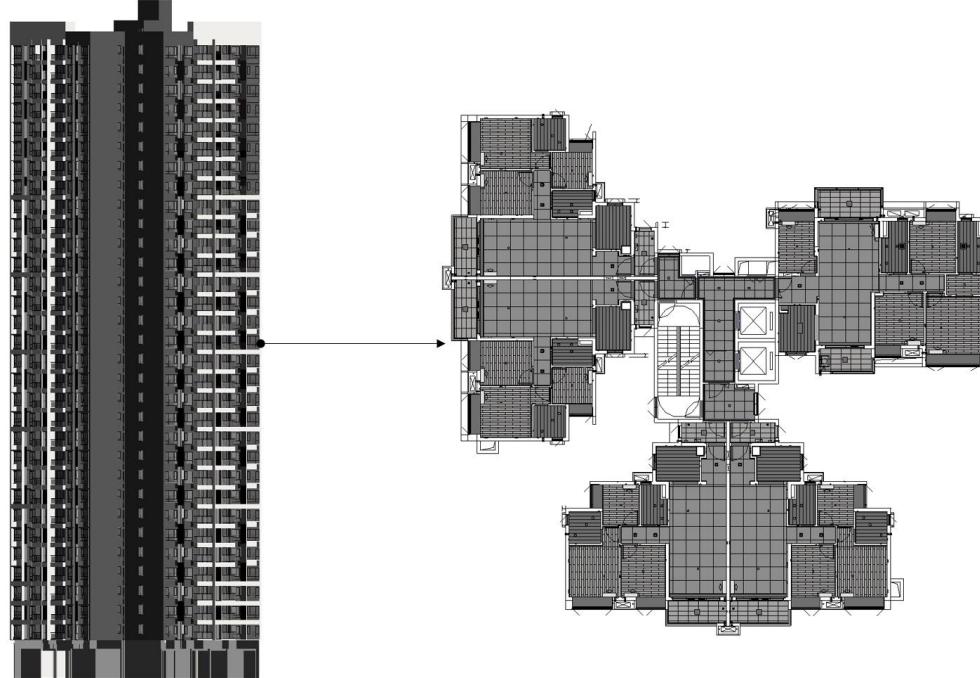


Figure 5. A SCC residential project with its typical floor plan

Table 1. Activity instances with their types

No.	Construction activities	Activity-resource type				
		1	2	3	4	5
1	Setting out the building	✓				
2	Placing reinforcement		✓			
3	Removing suspended formwork			✓		
4	Chiseling		✓			
5	Welding positioning rebar			✓		
6	Binding rebar for column				✓	
7	Installing aluminum formwork for wall and column					✓
8	Carcassing for wall					✓
9	Installing aluminum formwork for beam and slab				✓	
10	Binding rebar for beam and slab			✓		
11	Carcassing for slab					✓
12	Adjusting the formwork				✓	
13	Pouring concrete			✓		
In total		4	1	3	3	2

Table 2 shows the manpower resource planned which the schedule control criteria of each typical floor is finished 5 days. The client of this SCC project want to shorten the critical path by requiring each typical floor should be finished within 4 days, with the emphasis on faster capital turnover. The results

of the manpower resource planned due to the change of the schedule control criteria are showed in Table 3, as the work quantity and project quota remain the same. Comparing these two manpower resource plans, the resource change happened within the three activities: installing aluminum formwork for wall and column, installing aluminum formwork for beam and slab and adjusting the formwork. It can also be found that all resource changes are only available within type 4, in which the formwok workers are required to be designated and cannot be occupied with other activities. Otherwise, the duration to finish each floor's related work will be affected and the starting time of overlapped activities belongs to masonry and plastering group would be postponed because of their interdenpendency. As the results, the overall length of the critical path would be longer than the scheduled ones.

As presented in this case study, even only analyzing the manpower resource of main structure activity group for only one typical floor, it require the construction managers to identify all the project information related to activity's object and action (e.g., quantity and standardized start sequence), distinguish different activity-resource types, interprete them and analyze how they affect resource allocated manually. As the example discussed in the above case, critical resources will be affected by the scheduled length of the overall critical path. This practice is not effective since it is time-consuming and for construction manager to repeat this process for each activity. It can also be error-prone and cause discrepancies among different types of resource planning due to inconsistent identification of information and input. To overcome this challenge, this research suggests leveraging activity modeling by representing the required activity information, then the automated resource planning system can be developed to generate the project-specific instances of those resources within it. Such an method will also simultaneously involves information such as the SCC schedule data. Therefore, if this innovative method is available, once the construction manager simply represent the activity, the resource planned can also be updated quickly according to changes in schedule or others.

Table 2. Main structure group activities of a typical floor (5 days per floor)

No.	Activity	Schedule					Manpowe r resource quantity
		1 0. 5	2 0. 5	3 0. 5	4 0. 5	5 0. 5	
1	Setting out the building	X					2
2	Placeing reinforcement	X					2
3	Removing suspended formwork	X					6
4	Chiseling	X					2
5	Welding						
6	positioning rebar	X					2
	Binding rebar for column	X	X				13
	Installing aluminum						
	formwork for wall						
7	and column		X	X	X		20
8	Carcassing for wall			X			8
	Installing aluminum						
	formwork for beam						
9	and slab			X	X	X	20
10	Binding rebar for beam and slab				X	X	13

11	Carcassing for slab	X	8
12	Adjusting the formwork	X X X	23
13	Pouring concrete	X X	15

Table 3. Main structure group activities of a typical floor (4 days per floor)

No.	Activity	Schedule								Manpower resource quantity
		1 0.5	2 0.5	3 0.5	4 0.5	1 0.5	2 0.5	3 0.5	4 0.5	
1	Setting out the building	X								2
2	Placeing reinforcement	X								2
	Removing suspended									
3	formwork	X								6
4	Chiseling	X								2
	Welding positioning									
5	rebar	X								2
	Binding rebar for									
6	column	X	X							13
	Installing aluminum									
	formwork for wall and									
7	column	X	X							25
8	Carcassing for wall			X						8
	Installing aluminum									
	formwork for beam and									
9	slab			X	X					25
	Binding rebar for beam									
10	and slab					X	X			13
11	Carcassing for slab						X			8
12	Adjusting the formwork					X	X			30
13	Pouring concrete					X	X			15

5. CONCLUSIONS

Current practice of SCC resources planning is mainly based on construction manager's manual estimation. Generally, there are no methods available to enable automated resources planning to help construction managers in SCC project. Automated resource planning can provide a fast and consistent allocation of resources including manpower, machine, and material, which are directly related to construction cost. Hence, when inconsistent resource allocation across different planners, it can also provide a new control baseline for client to make better decisions.

This study, in which review current literature and practice, have identified six characteristics of SCC activities and defined 192 activity-resource types based on those characteristics. These activity-resource types, which affect the resource planning, are required to differentiate for SCC project. This finding provides a basis and motivation for further research in modeling SCC activities and automation in resource planning. With the development of automated resource planning for SCC projects, it is possible to achieve optimum planning by quickly and consistently analyzing those resource allocated.

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Causes of Delay in Tall Building Projects in GCC Countries

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Abstract: The 21st century is witnessing a rapid growth of tall buildings in urban centers globally to create more urban space for an anticipated urban population. Tall buildings, however suffer from incessant delays and sometimes total abandonment. Consequently, this study investigated and ranked the causes of delay in tall building projects, while focusing on the Gulf Cooperation Council (GCC) countries. Initially, 36 common delay causes investigated globally were categorized into 9 groups, and then further ranked utilizing the Relative Importance Index (RII) through a questionnaire survey. Tall building professionals in the GCC countries (Saudi Arabia, United Arab Emirates, Bahrain, Kuwait, Oman and Qatar) were contacted. The respondents' categories include Consultants, Contractors, and Clients' Representatives/Facility Managers. The results reveal that the top three causes include "client's cash flow problems/delays in contractor's payment", "contractor's financial difficulties", and "poor site organization and coordination between various parties". The findings from this study could help construction professionals develop guidelines and controls for delay mitigation, as well as support them in risk-based decision making in the planning of tall building projects.

Key words: tall buildings, gulf cooperation council, construction delays, high-rise buildings

1. INTRODUCTION

Tall buildings have been viewed as a viable solution to creating urban space in areas where there exists concentrated population, scarcity of land, and high land costs. Thus, the current trend is to take advantage of the urban skyline, and as a result, urban centres around the world now feature a huddle of tall building structures [1]. The construction industry, despite its continuous boom is still lagging behind other industries such as the aerospace, automotive and ship building industries. Unfortunately, the fundamental principles of construction have not changed for hundreds of years. Some of the factors influencing this drawback has been identified to include: the continuous fragmentation of the construction industry, globalization of construction, inadequate resources, the need for quality improvement, amongst others.

Problem areas in the construction industry are even more aggravated in the perspective of large construction projects such as tall buildings. In fact, tall building projects can be classified under the general category of large construction projects which are subject to delays [1]. Stakeholders in the industry unanimously agree that the success of a project is determined by the triple constraint of time, cost and quality. Interestingly, the Council on Tall Buildings and Urban Habitat (CTBUH) in its report "Dream Deferred: Unfinished Tall Buildings" noted the alarming rate of increase of "never completed" tall buildings, and further provided a list of 50 projects of 150m or taller that were never completed [2].

At this point, it is noteworthy to mention that there is a gamut of studies addressing the subject of construction delays in the research domain. These studies can be described as country/location and project specific, and the variations in causes of construction delays may be attributed to cultural influences, manpower availability, political instability, project contractual relationships, as well as other factors that are unique to various locations as well as project types [3]. Remarkably, there are limited studies that explore the causes of delay in tall building projects. Experts are of the opinion that identifying the causes of delay, though exploratory in nature, is the first step in mitigating the risk of delays. Some of the studies [4]–[10] that exist are either outdated, or are specific to a regional construction context, and thus it is required that further studies be carried out to explore the phenomenon of construction delay in other construction climates. Remarkably, countries in the GCC have witnessed a surge in tall building projects due to ambitious development plans in infrastructure and facilities with billions of US Dollars in investment [11]. This rapid growth in the region has positioned the GCC as a global leader in tall building construction. Tall buildings in the context of this research is considered as per the definition of The Council of Tall Buildings and Urban Habitat (CTBUH). CTBUH defines a tall building as one exceeding 50m in height, while supertall buildings exceed 300m in height, and mega-tall building exceeding 600m in height [12].

In light of the foregoing, the main objective of this research was to investigate, categorize and rank the causes of delay in tall building projects using the GCC countries as a case study. The study has significant implications for professional practice in delay risk mitigation as well as promote further research in other construction climates. The remainder of this manuscript presents a review of relevant literature, followed by the methodology, the results and findings, a discussion section, and finally conclusions of the study.

2. LITERATURE REVIEW

The following sections present a brief discussion on the history and evolution of tall building structures in the urban habitat. It also highlights some of the challenges faced by this type of structures, especially the occurrence of delays, and finally summarizes previous work related to construction delays in tall building projects.

2.1 Evolution of Tall Buildings in the Urban Habitat

Humankind has always been fascinated with tall buildings. Ancient structures such as the Tower of Babel, Colossus of Rhodes, the pyramids of Egypt, Mayan temples of Mexico, the Kutub Minar of India and many more were built to show power, pride and probably economic strength [12]. Even today, tall buildings are still the fascination of many nations globally. However, a host of other factors determines the need for tall buildings today. Significantly, global urbanization trends pose the challenge of an increasing pressure on urban housing and infrastructure. According to the United Nations (UN), urbanization will add another 2.5 billion people to urban populations by 2050. It is predicted that global population will rise up to 9 - 11 billion people [13]. Thus, urbanization and population are two parallel trends that suggest the need to optimize already limited resources to develop sustainable solutions for the safety and comfort of the world's future urban population. Experts are of the opinion that the continuous evolution of tall buildings fits the overall urban sustainability agenda as an inevitable housing solution [14].

Though, the origins of tall buildings in the urban context is evident in many urban cities such as Shibam in Yemen, which is a third century mud brick city with a density of around 300 per hectare, where most buildings are 8 storeys high [15]. The modern tall building traces its origin to the Home Insurance Building, a 10-story steel-framed structure built in Chicago in 1885. The following years witnessed an enthusiastic progression in the development of tall buildings until the Great Depression and World War II years. The drive for building tall re-emerged in the 1960s and has grown steadily into the 21st century. Today, urban centers around the globe are witnessing a rapid re-configuration of the urban skyline. The diversity of such global trend is witnessed in the level of development occurring in places like Shanghai, Shenzhen, Hong Kong, Dubai, Riyadh, Mumbai, London, to name only a few [16]. Most of the development is occurring in booming economies in Asia. China in particular, have massively increased the volume of tall building construction. According to the Council on Tall Buildings and Urban Habitat, of the 143 buildings over 200 meters high completed in 2018, 88 were in China. Similarly, Hong Kong and Singapore are distinguished by their high-rise public housing developments. Besides population growth and urbanization, these countries are also characterized by limited land

space, factors which have encouraged these cities to celebrate vertical development. Thus, over a period of 40–50 years, tall buildings have become the dominant building form and life style of the population. For instance, people are used to living in as high as the 40th storey in Hong Kong, while 84% of Singapore's resident population live in tall buildings [14].

2.2 Delays in Tall building Projects

While it is generally acknowledged that tall buildings are a viable solution to urbanization challenges of the 21st century, these buildings also suffer from underperformance issues such as delays. Abinu and Jagboro [17] define delays as situations where a project's completion time is postponed due to causes that may be related to the client, consultant, and contractor etc. Delays can also be defined as situations where an event occurs at a time later than expected, or to be performed later than planned; or not to take timely actions; or occurring beyond the agreed date specified in the contract. Delays in construction projects have potentially negative effects to all stakeholders including disputes or legal battles in court, cost and time overruns, loss of productivity and revenue, and contract termination [3]. The ambitious and risky nature of tall building projects, has led to a trail of abandoned projects across the globe.

2.2.1 Previous Studies on the Causes of Delay in Tall building Projects

The extant literature is saturated with studies investigating the causes of construction delay. Sanni-Anibire et al., [3] presented a systematic review of construction delay studies carried out globally. These studies were categorized as country/location and project specific. The following is a brief description of previous studies relating to tall building projects.

A pioneer study was carried out by Ogunlana et al., [4] to identify the delays experienced in high-rise building construction projects in Bangkok, Thailand. Structured and unstructured interviews of 30 professionals in 12 construction sites was made, and consequently, 26 causes of delay were identified. The study suggested that developing economies such as Thailand are prone to delays related to: “problems of shortages or inadequacies in resources”, “problems caused by clients and consultants” and “problems caused by contractor incompetence/inadequacies”. Likewise, Suksai et al., [6] explored the causes of delay in high-rise buildings in Bangkok and its vicinities. Accordingly, sixty three contractors were contacted through questionnaires and interviews. The study concluded that the main causes include “not working together to look as team-work”, “delayed delivery area to owner”, and “delay approval of drawings and list of construction”. Kaming et al., [5] studied the impact of construction time and cost overruns in high-rise construction projects in two Indonesian cities: Jakarta and Yogyakarta. The study identified seventeen variables from previous studies causing construction delays and cost overruns. Interviews were carried out with thirty-one project managers working on high-rise construction projects. The study suggested that the main causes of delays were “design changes”, “poor labor productivity” and “inadequate planning”. Bhangale, [7] investigated the causes of delay in high-rise building projects in Pune, India. The study reviewed various government reports and suggested that approvals as well as requirements to be fulfilled by developers or builders were the major factors causing delays. A more exploratory research was made by Aaditya and Bhattacharya, [10] on the causes of schedule overruns in high-rise building projects in various cities in India. The study employed a structured questionnaire to obtain the opinions of experts working on real estate high-rise projects in Bangalore, Kolkata, Mumbai and National Capital Region (NCR). The survey contained sixty seven factors of delay, and responses were obtained from 433 participants. The study concluded that the main causes of delay for all locations studied included “material quality”, “labor productivity”, and “skilled labor availability”. Haslinda et al., [8] investigated the factors influencing time and cost overruns for high-rise construction projects in Penang, Malaysia. The study adopted the questionnaire used by Kaming et al., [5], and feedback was obtained from thirty project managers involved in high-rise building projects in Penang. The study concluded that the most predominant causes were due to “design changes”, “inadequate planning and scheduling” and “poor labor productivity”. Kog [9] sought to explore other research methods as alternatives to questionnaire surveys, and thus reviewed records of 184 high-rise apartment blocks of the public housing agency in Singapore. The study concluded that the “late release of site”, “variation orders”, “delay by other contractors”, “shortage of building materials”, “inclement weather”, and “others (amenities and facilities not ready)” were the main factors responsible for delay.

3. METHODOLOGY

The methodology employed in this research can be summarily categorized as follows:

3.1. Stage 1: review of the extant literature

A review of literature was carried out to identify the main causes of construction delay to be investigated in this study. Firstly, 11 influential studies were identified for the purpose of outlining the causes of delay. The studies were selected based on their publication in the last 15 years, and high number of citations-an indication of their prominence in the research landscape. Consequently, 36 causes of delay were identified and grouped into nine categories in line with other similar studies.

3.2. Stage 2: Questionnaire design and administration

The identified causes of delay were used to develop a standard questionnaire survey for obtaining the feedback from industry experts. A Likert scale of importance from 1 to 5 was used to design the questionnaire in line with previous studies investigating the causes of delay. Where 1 represents: Least Important (LI), 2: Slightly Less Important (SLI), 3: Moderately Important (MI), 4: Very Important (VI), and 5: Extremely Important (EI). The questionnaire contained three parts, where the first part was meant to obtain demographic information on the respondents, the second part was meant to obtain their feedback on the levels of importance of the various causes of delay, and the third part was meant to obtain open-ended feedback from the respondents. The respondents' categories included Consultants (including Architecture, Structure, Mechanical, Electrical and Plumbing (MEP), and Project Management (PM)), Contractors and Clients' Representatives/Facility Managers. Various strategies were used in distributing the questionnaire survey, this entailed hand delivered hard copies to managers at tall building construction sites, as well as through emails of a web-based format to tall building professionals in the GCC countries. These countries include Saudi Arabia, United Arab Emirates, Bahrain, Kuwait, Oman and Qatar. Since, it is not possible to ascertain the number of tall building professionals in the GCC region, the sample collection was based on the philosophy of "use as many subjects as you can get and you can afford" [19]. Moreover, Fellows and Liu [20], suggest that "large number" statistics require a sample size equal to or greater than 32. The sample size is also comparable to similar studies as presented in previous sections.

3.3. Stage 3: Analysis of Results

To test the reliability of the questionnaire, the standardized Cronbach's alpha (α) test was employed. In general, a range of (0.7 to 1.0) may be considered satisfactory [21]. Higher values denote greater internal consistency and vice versa. Mathematically, α is calculated as follows:

$$\alpha = \frac{K\bar{r}}{(1+(K-1)\bar{r})} \quad (1)$$

Where K is the number of components in the test; and \bar{r} is the mean of the triangular correlation matrix. Doloi [22] provides the following scale as a rule of thumb: $\alpha > 0.9$ denotes excellent, $0.9 > \alpha > 0.8$ as good, $0.8 > \alpha > 0.7$ as acceptable, $0.7 > \alpha > 0.6$ as questionable, $0.6 > \alpha > 0.5$ as poor and $0.5 > \alpha$ denotes unacceptable.

Data analysis of the retrieved questionnaire survey was made using the Relative Importance Index approach similar to previous studies. The use of the RII methodology in this research was to identify and rank the most important causes of delay. The RII also promotes the possibility for comparison of the results from various studies. Moreover, researchers are of the opinion that the mean and standard deviation of each individual attribute is not a suitable measure [22], [23]. The RII calculation considered in this study is presented as follows [3]:

$$RII = \frac{\sum_{i=0}^n (a_i)(x_i)}{n \sum x_i} \quad (2)$$

Where a_i is the constant representing the weight assigned to i (ranges from 1 to n); and x_i is the variable representing the frequency assigned to i (ranges from 1 to n).

To determine the level of agreement between various respondent categories, Spearman's rank correlation coefficient (r_s) was employed in conformance with previous studies [23]. The rank of various causes of delay according to the Consultants (Architecture/Structure/MEP/PM), Contractors, and

Clients' Representatives/Facility Managers was determined and utilized as inputs. Mathematically, Spearman's rank correlation coefficient (r_s) is calculated as follows:

$$r_s = 1 - \frac{6 \sum d^2}{n(n^2 - 1)} \quad (3)$$

Where d is the difference between the ranks indicated by two respondent groups, and n is the number of records. The value of the Spearman rank correlation coefficient ranges from +1 (perfect correlation), to 0 (no correlation), to -1 (perfect negative correlation).

4. RESULTS AND FINDINGS

4.1 Respondents profile and questionnaire's reliability

The demographic information of the respondents in this study is presented in figure 1, respondents were composed mainly of senior professionals in three categories (consultants, contractors and client representatives/facility managers) practicing in the GCC countries. Respondents in the GCC (i.e. Saudi Arabia, United Arab Emirates, Kuwait, Bahrain, Oman and Qatar) were contacted through professional bodies, personal emails, as well hand delivered questionnaire surveys to tall building construction sites. A total of 62 responses were received, while 5 responses were discarded as unusable, due to being improperly filled or coming from professionals outside the GCC. Thus, a total of 57 responses were used in this study. The quality of the response is exemplified in the fact that only senior professionals in the organizations contacted provided were requested to provide their feedback. To test the reliability and consistency of the questionnaire survey, Cronbach's alpha was calculated to be 0.99, indicating an excellent reliability of the questionnaire survey. As shown in figure 1, the contractors represent 30% of the population, while the consultants represent 35%, and similarly the clients' representatives/facility managers. The figure also shows that 23% of the respondents were designated as project managers at the time of the survey, while 21% were holding facility manager roles, 15% director roles and 11% executive director roles. Majority of the respondents, representing 48%, had greater than 15 years of experience in tall building projects. UAE and Saudi Arabia, with 42% and 33%, represents the majority in terms of the location of the respondents. Feedback from the respondents showed that their professional experience spans various types of tall building projects including residential, commercial, hotels, multi-use as well as other types of facilities.

4.2 Relative Importance Index and ranking of delay causes

As established previously, the RII approach is the most popular method used in studies on the causes of construction delays. In this study, the RII values have been presented according to three professional categories including the consultants, contractors and clients' representative/facility managers. Additionally, the overall RII value combining the three professional categories are also presented as shown in table 1. Table 1 also presents the RII values and rankings for the 9 groups. It can be seen from table 1 that the top five causes of delays in tall building projects include: Fin. 2: "client's cash flow problems/delays in contractor's payment"; Fin. 1: "contractor's financial difficulties"; Sch. 1: "poor site organization and coordination between various parties"; Cont. 1: "inappropriate construction/contractual management/construction methods"; and Sch. 7: "poor qualification of the contractor or consultant". Similarly, the last 5 causes in ascending order include: Env. 2: "civil disturbances/hostile political conditions"; Env. 1: "weather condition"; Man. 3: "labor disputes and strikes"; Mat. 1: "shortage in construction materials/unforeseen material damages"; and Chng. 4: "unexpected foundation conditions encountered in the field". The table also shows that the most significant group of delay causes is the "causes related to financing" group, with an RII value of 0.82.

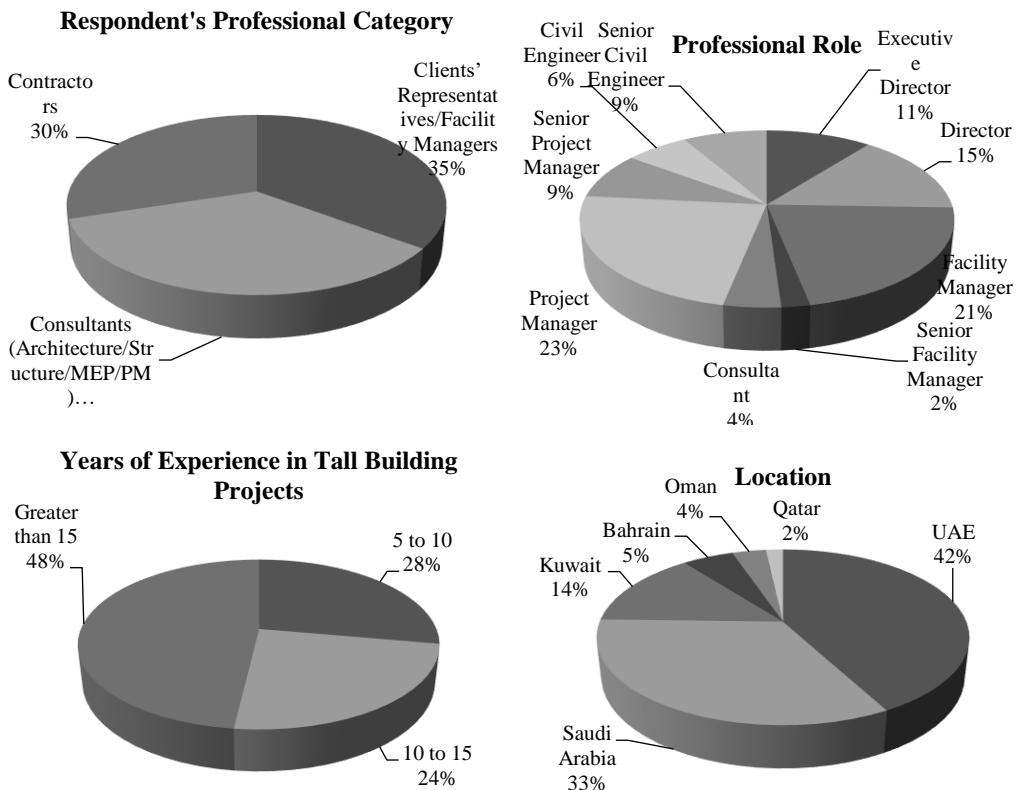


Figure 1. Demographic information of respondents

Table 1. Relative Importance Index and ranking of the causes of delay

S/ N	Causes of delay	Consultants		Contractors		Clients' Representative s/Facility Managers		Total	
		RII	Rank	RII	Rank	RII	Rank	RII	Rank
	Causes related to material	0.68	7	0.8	3	0.75	4	0.74	5
1	Mat. 1 Shortage in construction materials/unforeseen material damages	0.67	31	0.77	14	0.7	27	0.71	32
2	Mat. 2 Slow delivery of materials	0.71	27	0.86	3	0.74	18	0.76	18
3	Mat. 3 Waiting for approval of shop drawings and material samples	0.67	31	0.77	14	0.8	8	0.75	21
	Causes related to manpower	0.75	5	0.69	8	0.74	5	0.73	6
4	Man. 1 Shortage in manpower (skilled, semi-skilled, unskilled labor)	0.81	9	0.77	14	0.74	18	0.77	13
5	Man. 2 Poor labor productivity	0.8	13	0.71	31	0.79	14	0.77	14
6	Man. 3 Labor disputes and strikes	0.64	34	0.6	35	0.69	30	0.65	34
	Causes related to equipment	0.72	6	0.72	7	0.74	5	0.73	6
7	Equip. 1 Poor equipment productivity (breakdown/maintenance problem)	0.71	27	0.73	27	0.74	18	0.73	27

8	Equip. 2	Shortage in equipment	0.73	23	0.7	33	0.74	18	0.72	28
Causes related to contractual relations			0.79	2	0.78	4	0.78	2	0.78	2
9	Cont. 1	Inappropriate construction/contractual management/construction methods	0.83	5	0.83	6	0.83	5	0.83	4
10	Cont. 2	Slowness in decision making	0.84	3	0.8	9	0.73	22	0.79	12
11	Cont. 3	Delay in mobilization	0.67	33	0.73	27	0.76	16	0.72	30
12	Cont. 4	Excessive bureaucracy/interference by the owner	0.82	7	0.79	10	0.72	23	0.77	14
13	Cont. 5	Delay in approval of completed work	0.73	22	0.78	11	0.8	8	0.77	16
14	Cont. 6	Delay in sub-contractors work	0.83	4	0.76	18	0.81	6	0.81	8
Causes related to government			0.79	2	0.81	2	0.76	3	0.78	2
15	Gov. 1	Slow permits from municipality/government	0.81	11	0.83	5	0.8	8	0.81	7
16	Gov. 2	Government regulations	0.77	19	0.78	12	0.71	24	0.75	19
Causes related to financing			0.81	1	0.84	1	0.83	1	0.82	1
17	Fin. 1	Contractor's financial difficulties	0.81	11	0.85	4	0.9	1	0.85	2
18	Fin. 2	Client's cash flow problems/Delays in contractor's payment	0.9	1	0.89	1	0.88	3	0.89	1
19	Fin. 3	Price escalation/fluctuations	0.72	24	0.78	12	0.7	27	0.73	26
Causes related to environmental factors			0.59	8	0.63	9	0.59	7	0.59	7
20	Env. 1	Weather condition	0.58	36	0.65	34	0.59	35	0.6	35
21	Env. 2	Civil disturbances/Hostile political conditions	0.61	35	0.6	35	0.58	36	0.59	36
Causes related to changes			0.77	4	0.77	5	0.73	6	0.76	4
22	Chng. 1	Design errors/incomplete made by designers (Architects and structural drawing)	0.82	8	0.86	2	0.75	17	0.80	9
23	Chng. 2	Design variations/change orders/increase in scope of work	0.83	6	0.83	6	0.8	8	0.82	6
24	Chng. 3	Errors committed due to lack of experience	0.79	15	0.75	19	0.81	6	0.79	11
25	Chng. 4	Unexpected foundation conditions encountered in the field	0.71	27	0.74	25	0.69	31	0.71	32
26	Chng. 5	Changes in materials types and specifications during construction	0.78	18	0.74	25	0.69	31	0.74	23
27	Chng. 6	Inaccurate site/soil investigation	0.72	24	0.75	19	0.68	34	0.71	31
28	Chng. 7	Frequent change of sub-contractor	0.75	21	0.75	19	0.69	31	0.73	25
Causes related to scheduling and controlling techniques			0.78	3	0.75	6	0.78	2	0.77	3
29	Sch. 1	Poor site organization and coordination between various parties	0.87	2	0.75	19	0.89	2	0.85	3

30	Sch. 2	Poor planning of resources and duration estimation/scheduling	0.81	9	0.77	17	0.8	8	0.79	10
31	Sch. 3	Inadequate supervision, inspection and testing procedures	0.79	16	0.71	32	0.78	15	0.76	17
32	Sch. 4	Accidents during construction/lack of safety measures	0.68	30	0.72	29	0.8	8	0.74	22
33	Sch. 5	Poor communication/documentation and detailed procedures	0.77	20	0.72	29	0.71	24	0.73	24
34	Sch. 6	Unrealistic time schedule imposed in contract	0.8	13	0.75	19	0.7	27	0.75	19
35	Sch. 7	Poor qualification of the contractor or consultant	0.79	16	0.83	6	0.86	4	0.83	5
36	Sch. 8	Architects'/structural engineers' late issuance of instruction	0.72	26	0.75	19	0.71	24	0.72	29

4.3 Test of Agreement between Various Groups

The Spearman rank correlation coefficient has been used by other similar studies to test the level of agreement between parties and groups of respondents. In this study, the correlation between consultants and contractors, consultants and client's representatives/facility managers, and contractors and client's representatives/facility managers were 0.58, 0.55 and 0.47 respectively. These results indicate a moderate level of agreement between all parties. More specifically, the contractors and client's representatives/facility managers had the least level of agreement. This may be attributed to widely opposing views between both parties during the project life cycle, and especially during the testing and commissioning process which delays handover of the project to the client's representatives/facility managers.

4.4 Open-ended response on the questionnaire survey

The open ended section of the questionnaire survey was used to derive more qualitative feedback from respondents on the causes of delay. The crucial areas leading to delays may be summarized as follows:

- Poor project management and dispute resolution skills.
- Increasing complexity in tall building designs.
- Lack of engagement with the supply chain early in the process.
- Poor contract administration and contractor selection process.
- Poor technical capabilities of the clients' representatives.
- Redesign and rework due to poor coordination of MEP systems with other systems.
- Delay in handover process due to lack of involvement of the end-use/facility manager from the project inception stage.
- Lack of competence critical to technologies in modern projects such as digital twin.
- Preference for imported materials-which are delivered late-over locally available materials.
- Change in key client personnel.
- Major changes in the use, shape or facade of buildings requiring re-design/checking already constructed elements.

5. DISCUSSION

The construction industry for many decades has been plagued with inefficiency and productivity losses, amongst which are incessant delays in large building projects. Therefore, the research domain features an abundant amount of literature in identifying the causes of construction delays. These studies can be classified as either country/location specific or project specific [3]. Though, such construction

delay studies are exploratory in nature and do not provide the ultimate solution needed by the industry [1], experts are of the opinion that identifying the causes of delay is the first step in developing effective solutions to mitigate them. Despite the huge amount of work that predominate, not much attention has been accorded to delays that occur in tall building projects. The significance, of tall buildings in the urban context is in its potential to be a viable solution to an impeding housing crisis. Interestingly, these buildings have been subject to incessant delays and total abandonment, and thus defeating their objective as a sustainable solution. Notably, CTBUH outcries the increasing rate of tall building abandonment, while providing a list of 50 projects of 150m or taller that were never completed [2].

This study thus explores the causes of delay in tall building projects, using countries in the Gulf Cooperation Council as a case study. Firstly, 36 major causes of delay were identified from influential studies carried out across the globe [3]. These causes were further assessed by senior level construction professionals in the GCC countries. The results showed that the most significant cause of delay was related to financial issues which conforms to the global trend on delay causes. Tall buildings are viewed as risky investments, and thus, suffer from cost overruns, time overruns and ultimately abandonment of the project. This study also showed that delay causes such as “weather condition” may be prevalent in other countries such as Singapore [9], it is perceived as not contributing to significant delay in the GCC region. This may be largely due to the arid nature of the region, where rainfall occurs few times in the year. Likewise, delay causes such as “civil disturbances/hostile political conditions”, “labor disputes and strikes”, “shortage in construction materials/unforeseen material damages”; and “unexpected foundation conditions encountered in the field” were perceived as the least causes contributing to details. Further qualitative feedback from the respondents hinted that tall building projects are subjected to extensive soil and foundation studies such that “unexpected foundation conditions encountered in the field” is unacceptable, and usually does not occur. This study also shows how the causes of delay in tall building projects may vary with respect to the construction climate under investigation. Significant implications for research and practice may be derived from this study. For professional practice, it could form the basis for developing guidelines and recommendations, as well as project control and monitoring strategies for tall building projects. Furthermore, real estate investors could use the causes of delay identified in financial risk assessments in project feasibility studies. As for the research implications, it would be interesting to see how the results of this study will compare to further studies from China and the USA, where there has been rapid development of tall buildings in the past few decades.

5. CONCLUSION

The proliferation of tall building structures in urban centers across the globe is sufficient evidence that the urban built environment is witnessing a paradigm shift centered on sustainability and efficiency. This building type however suffers from delays and total abandonment. Thus, this study sought to investigate the causes of delay in tall building projects in the GCC countries. The results showed that the top three causes of delay include “client’s cash flow problems/delays in contractor’s payment”; “contractor’s financial difficulties”; and “poor site organization and coordination between various parties”, while the most significant group causing delay is the “causes related to financing” group. Notably, the study revealed that delay causes such as “civil disturbances/hostile political conditions” and “labor disputes and strikes” were perceived as relatively insignificant in the GCC countries. Furthermore, “unexpected foundation conditions encountered in the field” was considered as an unlikely cause of delay in tall building projects, as soil and foundation investigations are considered critical aspects of tall building projects. The contribution of this study is in the assessment of major delay causes in tall building projects, a fast rising construction phenomenon in the 21st century. Understanding the causes of delay is recognized as the first step towards mitigation and control. It is hoped that the results of this study will be carried over to professional practice in delay risk mitigation, as well as further research in other construction climates.

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III. BIM-ENABLED AEC APPLICATIONS I (A3)

BIM-based Lift Planning Workflow for On-site Assembly in Modular Construction Projects

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Abstract: The assembly of modular construction requires a series of thoroughly-considered decisions for crane lifting including the crane model selection, crane location planning, and lift path planning. Traditionally, this decision-making process is empirical and time-consuming, requiring significant human inputs. Recently, research efforts have been dedicated to improving lift planning practices by leveraging cutting-edge technologies such as automated data acquisition, Building Information Modelling (BIM) and computational algorithms. It has been demonstrated that these technologies have advanced lift planning to some degree. However, the advancements tend to be fragmented and isolated. There are two hurdles prevented a systematic improvement of lift planning practices. First, the lack of formalized lift planning workflow, outlining the procedure and necessary information. Secondly, there is also an absence of a shared information environment, enabling storages, updates and the distribution of information to stakeholders in a timely manner. Thus, this paper aims to overcome the hurdles. The study starts with a literature review in combination with document analysis, enabling the initial workflow and information flow. These were contextualised through a series of interviews with Australian practitioners in the crane-related industry, and systematically analysed and schematically validated through an expert panel. Findings included formalized workflow and corresponding information exchanges in a traditional lift planning practice via a Business Process Model and Notation (BPMN). The traditional practice is thus reviewed to identify opportunities for further enhancements. Finally, a BIM-based lift planning workflow is proposed, which integrates the scattered technologies (e.g. BIM and computational algorithms) with the aim of supporting lift planning automation. The resulting framework is setting out procedures that need to be developed and the potential obstacles towards automated lift planning are identified.

Key words: Modular construction, BIM, Lift Planning, Crane, Construction automation

1. INTRODUCTION

Over the past few decades, modular construction is increasingly prevalent around the globe. This innovative construction method has dramatically enhanced productivity and safety via manufacturing building modules in a controlled plant environment [1] and assembling them on-site. While the modular construction method greatly boosts the efficiency and productivity of the construction process, it increases the complexity in planning and managing on-site assembly processes, which usually involves large cranes lifting prefabricated construction modules. Since these modules to be lifted are typically large and heavy with complex geometries, the lift crew has to take extra care to avoid safety hazards such as collision and crane overturning. Meanwhile, crane-related tasks are critical to prefabrication projects management by significantly impacting the overall schedule and affecting budget implementation [2]. Therefore, meticulous lift planning is essential to mitigate risks and improve efficiency.

Traditional lift planning is a tedious and complex process, depending on planners' evaluations of the site, available crane models, and lifting tasks [23]. In most cases, this information is collected and managed by different stakeholders. For example, a regular crane operation typically involves five participants or participating organizations [12]. Correspondingly, the information from these stakeholders is kept on various physical and digital formats, such as spreadsheets, drawings or text files and exchanged via meetings, emails and handbooks. This exchange process is inefficient and often further prolongs the planning process with possible omissions and delays [17]. As a result, planners have to go through iterative cycles of coordination to retrieve necessary information for decision-making. Hence, the traditional lift planning process usually lasts for months [14]. On the other hand, planners heavily rely on their experience. Thus, the planners may not fully consider all possible scenarios and alternatives, leading to a suboptimal lift plan. These shortages make current lift planning a time-consuming and ineffective process.

Modern technologies have the potential to advance lift planning practices. As a new paradigm in managing construction projects, Building Information Modelling (BIM) is capable of harmonizing information exchanges between different stakeholders in a timely and concise manner [19]. For example, researchers have defined the workflow of design and engineering to coordinate the collaborations among architects and engineers [3,4]. Another widely adopted technology is the planning algorithm. Researchers have proposed numerous algorithms to automate and optimize some lift planning decisions such as crane model selection [5], crane positioning [6], path planning [7], and crane stability design[8]. Thirdly, technologies in acquiring real-time construction data have been evolving in terms of efficiency and accuracy, such as laser scanning and GIS [9,10].

Recognizing the limitations of existing lift planning practices and the opportunities presented by new technologies, this paper presents a new workflow that integrates cutting-edge technologies to acquire, manage and analyse lift-related information. The study is presented as follows: Section 2 presents a thorough literature review on the traditional lift planning process and advanced information technologies employed to assist in current lift planning practices. This is followed by Section 3, describing the research methodology. Section 4 implements the methodology to formulate the innovative workflow. Both traditional and innovative lift planning workflows are illustrated with BPMN models and the necessary information exchanges are identified. Section 5 discusses the benefits and barriers to fulfilling the newly proposed lift planning workflow and concludes the study.

2. LITERATURE REVIEW

As introduced in the previous section, lift planning has a workflow involving multiple stakeholders and comprising several decision-making tasks. Thus, the foremost mission of this study is to clarify the traditional lift planning workflow (section 2.1). The traditional lift planning workflow consists of multiple decisions. In this study, the decision-making processes are abstracted as three modules: information acquisition, information management and decision making. All three modules have been advanced by modern technologies, which is introduced in section 2.2 to 2.4. Since previous research has focused on the application of individual technology, the literature review is expected to enable the formulation of a new workflow utilizing new technologies.

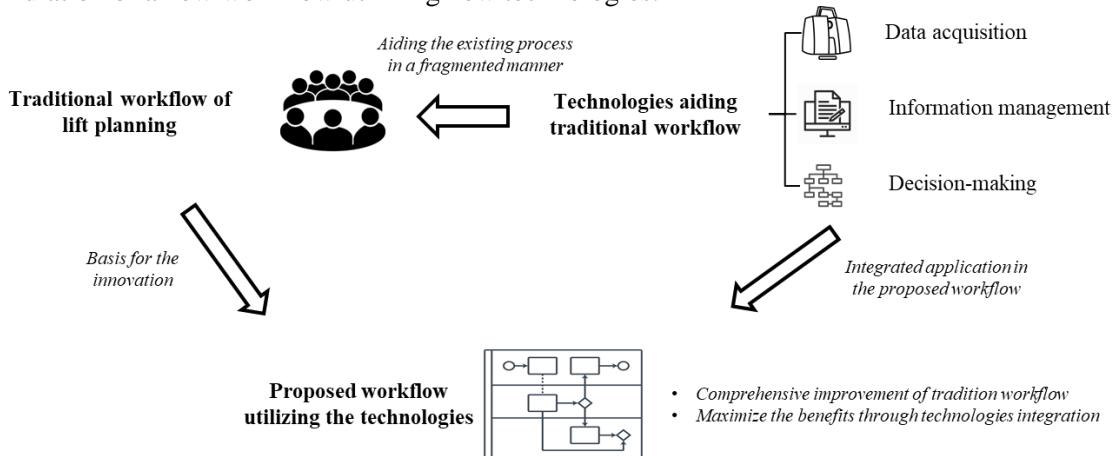


Figure 1. Overview of the relationship between traditional workflow of lift planning, lift planning aiding technologies and the proposed workflow

2.1. Traditional lift planning

Lift planning is a complex task consisting of multiple decisions made through the collaboration of various stakeholders [12]. For example, the site geometric data is collected by the site management team and the crane hire company. Then, the information is exchanged between data collectors and decision-makers so that the decision makers can apply their professional knowledge. In a traditional lift planning process, site geometric data is acquired by manual surveying, managed via 2D drawings, and analysed based on experiences. Therefore, the information is not accurate, comprehensive nor up-to-date.

The traditional lift planning workflow involves many stakeholders and their responsibilities are overlapped in some cases. Thus, many countries formulated standards to specify the stakeholders related to crane operations and their responsibilities. Among the standards, US ASME B30 [12] standards covered most of the roles defined in other standards and further described the respective responsibilities of the crane owner, the crane user, the site supervisor, the lift director, and the crane operator. In this particular paper, the crane owner is specified as the crane hire company and the crane user is specified as the project manager. In the lift planning practice, all stakeholder participates in the decision-making processes, where the major decisions are made by a certain stakeholder while others serve as information sources or reviewers verifying the planning result.

The process of tradition lift planning contains four tasks: (1) determining the type and quantity of cranes, (2) selecting competent crane model, (3) positioning the tower crane on-site and ensuring its stability, and (4) directing paths of individual lifting operations. The sequence has been observed in most lift planning practices, in spite that some tasks are combined in smaller projects. It is also noted that although the sequence exists, tasks are not isolated from each other. For example, in order to select an appropriate crane model, the planners have to know the distances between the supply area and the crane, which is calculated using the location of the supply area and the location of the crane; however, the location of the crane is not determined until the location planning task finishes. In such cases, traditionally lift planning process makes assumptions on unknown information and verify the assumptions in subsequent tasks.

2.2 Data Acquisition

As described in the previous section, information acquisition is the first step to any decision-making in the lift planning process. Traditional information acquisition is accomplished via a hand-operated survey. Recently, cutting edge sensing technology such as 3D laser scanning GIS and photometry technologies have been adopted to aid lift planning. Among the technologies, 3D laser scanning is widely adopted in current surveying practices [9]. Compared with its traditional counterpart, 3D laser scanning outperforms in terms of accuracy, efficiency and ease of communication. Thus, the use of laser scanning technology in construction applications is extensively investigated by researchers. For example, Chen et al. [9] used laser scanning to capture site geometry for tracking mobile assets. Cheng and Teizer [10] utilised laser scanner to measure as-built conditions and site environment. More recently, Goh et al. [11] simulated the lifting operation of critical components in a complex environment based on the authentic information obtained via laser scanning. Although the technology can accelerate tedious manual survey, the scanning results are usually imported as editable models [17]; thus efforts have to be made to convert formats to gain full operability. The reason for this phenomenon is that there lacks a common format accepted by all stakeholders, and each stakeholder has their preferred formats.

2.3 Information Management

Information management is another major interest area of research. Among many information management innovations, Building Information Modelling (BIM) is the most prevailing technologies in the AEC industry. BIM is defined as a digital representation of a facility, which shares knowledge and supports decisions during the entire building life-cycle [29]. The first step of implementing BIM in a certain domain is to specify the workflow of information exchanges, namely Information Delivery Manual (IDM). IDM is a process map denoting the necessary information to be exchanged between two stakeholders [32]. For example, Chuck Eastman et al. [19] generated the IDM for the precast concrete use case and enumerated the information exchanges. Later, efforts were made to consolidate information exchanges to eliminate redundancy and therefore, to enhance efficiency [20, 21]. The application of BIM in prefabrication construction, including modular construction, significantly improved the efficiency of information exchange [30]. However, the studies usually focus on the design and engineering phase, while construction activities such as lift planning are either omitted or oversimplified. For example, in the aforesaid IDM, the general contractor represents all the construction

stakeholders [25]. Additionally, construction equipment configurations have not been clearly defined. One of the obvious reasons is that most lift planning practices are carried out manually and empirically based on drawings and on-site investigations. Thus, construction stakeholders act as end-users, who receive information but provide limited feedback. Therefore, there is no demand to include detailed construction. Nevertheless, the demand grows with the extensive application of modular construction and the increasingly demanding lifting tasks.

2.4 Decision Making

In recent decades, researchers have investigated the potential of algorithms to automate and optimize lift planning. Many algorithms were created and reported for lift planning processes [16]. For the model selection task, some researchers aimed at formalizing the relative importance of selecting criteria and programmed them into an automated scoring system. For example, Han et al. [2] proposed a selection matrix to evaluate each option with scores. Similarly, Marzouk and Abubakr [5] created an analytical hierarchy process (AHP) to score the factors influencing crane type (e.g. Flat Top or Hammerhead tower crane) selection. Meanwhile, other researchers filtered infeasible solutions to narrow down the scope, whereby choose the optimal solution [26]. For example, Sohn et al. [18] adopted a generic algorithm to choose an economical crane model based on crane configurations and soil conditions.

For location planning task, algorithms were adopted to minimize the cost in regards to the crane's operating time [27]. The location planning problem was therefore simplified as finding the minimum of a function of the cumulative travelling time of loads to be lifted between the supply area and demanding points [28]. Various algorithms have been adopted to seek the minimum of the function. For example, Nadoushani et al. [6] developed a mixed-integer programming algorithm to find the lowest crane rental cost location; Lien and Cheng [16] modified the particle bee algorithm for tower crane layout problems, considering not only budget limit but the capacity of the supply area. It is observed that yielding an optimal result requires cost quotes for many activities and detailed crane configurations from the crane manufacturer; therefore complex information exchanges are inevitable. In this regard, Wang et al. [17] tried to use a BIM model as the source of inputs for algorithms' mathematical model and a visualisation tool. Although the paper took the advantages of BIM, manual information retrieval from spreadsheets and drawings was not eliminated. In other words, the potential of BIM has not been fully utilized.

For lift path planning, algorithms were adopted to find collision-free and efficient paths for lifting operations. Since path planning is a classic problem in robotics domain, plenty algorithms have been adopted for lift path planning, including Genetic algorithms GA [14], Rapid Random-exploring Tree (RRT) [15], and Probability Roadmaps (PRM) [24]. Compared with the traditional lift path planning process, these algorithms outperformed in finding the shortest collision-free paths and eliminated the worry for exceeding the rated capacity.

2.5 Summary

These data acquisition, information management and decision making technologies have navigated the lift planning towards high efficiency and optimization; however, they arose new problems. One of the problems is poor interoperability. For example, to use planning algorithms, a user may need to translate the schedule information from the traditional Gantt Chart to a matrix or an array in a certain programming language. However, the translation requires a quite specialized yet divergent skillset from the tradition, which is not commonly possessed by AEC practitioners. Therefore, applying new technologies causes extra cost and training time. In addition, new technologies only facilitated part of the activities in the lift planning process. Hence, a limited increase in the efficiency of the entire lift planning process is gained. These two problems reflected a more fundamental issue: there lacks an integrated workflow harmonizing the technology-aided lift planning activities.

According to the previous analysis, lift planning, as one of the increasingly important activities in construction, has the revolutionary potential with emerging information technologies. These technologies are expected to advance lift planning for all types of crane, regardless of tower cranes and mobile cranes. However, in real-world practices, planning activities for tower cranes and mobile cranes are not at this point yet. This difference attributes to their contrasting operating mechanics; for example, mobile cranes can change location during construction while tower cranes cannot. Thus, planning for tower cranes requires a more comprehensive and accurate set of information of all anticipated construction activities at the early project planning stage. This includes the more challenging development of the standardized workflow and information exchange protocol for tower crane lift planning. At a later stage, the workflow can be adapted to mobile crane lift planning.

3. RESEARCH METHOD

The literature review and document analysis of existing manufacture guidelines established an initial BPMN map and helped in identifying subject experts for interviews. Initially, the BPMN map was circulated for comments before a panel discussion with the Australian domain experts of the crane lifting industry established traditional practices as well as validated the set up for the technologically enhanced and integrated workflow.



Figure 2. Overview of the method to propose the new lift planning workflow

Focusing on lift planning for tower cranes, the research process followed a three-step method. Firstly, the authors organized a panel of domain experts in the crane lifting industry and based on their discussion, established the traditional lift planning workflow. The result was summarized using a Business Process Modelling Notation (BPMN) map. Secondly, the traditional lift planning BPMN was scrutinized and analyzed. Discussion items included the contents, the level of detail, the formats, the sources, and the exchanges of information. Meanwhile, the traditional workflow was also assessed in terms of efficiency, optimization, and coherence. Thirdly, the authors investigated the potential of aforesaid data acquisition, information management and decision making technologies and systemised them in an integrated workflow. The newly developed workflow was also reviewed and both the benefits and challenges were discussed, for description see Section 4.

4. BIM-BASED LIFT PLANNING WORKFLOW

4.1. Traditional lift planning workflow

Through the consultation with the lift expert panel, a traditional lift planning BPMN model has been developed. BPMN is a graphic representation of a business process, denoting the flow of activities and the corresponding information exchanges [31]. Frequently used symbols and notations of BPMN are illustrated in Figure 3. Afterwards, the traditional lift planning BPMN is demonstrated in Figure 4. This diagram streamlined the lift planning process as 4 phases: (1) crane quantity and type determination; (2) subcontracting; (3) jobsite positioning; and (4) lifting path planning. Concurrently, 7 participants were identified: the engineering firm, the fabricator, the project manager, the site supervisor, the crane hire company, the lift director and the crane operator.

Firstly, the project manager needs to ensure that the number of cranes satisfies the job requirement, time and budget. Then, the crane type is determined based on site spatial constraints such as the jurisdiction boundaries of the site, neighbouring structures and the height of the building. Consequently, each crane has fixed working radius and loads to be lifted. Among all loads to be lifted by a tower crane, the most critical load is determined based on size, weight and the distance between supply and demanding points, revealing the minimum rated capacity. The project manager sends the capacity and coverage requirements to the crane hire companies, who then visit the sites and communicate with the site supervisor for site conditions. After that, the crane hire companies nominate cranes with quotes to the project manager based on the inventory of cranes and lifting accessories. The quotes cover a wide range of costs, including direct costs incurred by hiring and indirect costs as associated with crane erection/dismantling and transportation. Finally, the crane configurations and quotes form a proposal which will be submitted to the project manager for approval. When it is approved, the site supervisor starts to deploy cranes on-site, aiming at determining the most efficient location for each crane and, thereafter, finalizing the detailed stability designs (e.g. crane base and tie-in anchorage). Finally, the lift director implements the decisions of the site supervisor and assigns lifting tasks to the crane operator. For the critical lifting tasks, the lift director and the crane operator convene a meeting to issue a formal lift plan; while for the routine lifting tasks, the crane operator directly determines paths, based on their experience.

In spite of lift planning workflow being described in a linear manner, the planning is actually conducted in a trial-and-error fashion. For example, the project manager has to make some assumptions, which cannot be verified until the site supervisor finishes crane positioning. Therefore, the actual information exchange network is way more complicated than it was described in the BPMN model. Meanwhile, the information exchanges are mainly conducted via untimely methods such as meetings and paperwork. Therefore, it consumes a considerable amount of time for a feasible plan. Due to the time constraints, it is nearly impossible to compare several feasible plans, let alone exhaust all possibilities in pursuit of the optimal plan, in the traditional format. Two main reasons for the oversophisticated decision-making process are the scattered information storage and overlapping functions. As shown in Figure 4, selecting a capable crane model needs to retrieve information from fabricator, the project manager, the site supervisor and the crane operator, who preserve information in their particular formats; and the decision-making function is shared by the crane hire company and the project manager, who do not always own a shared interest. Therefore, retrieving information and unifying the formats become an inevitable bottleneck of efficiency, along with the negotiations to coordinate the collaborative decision makers.

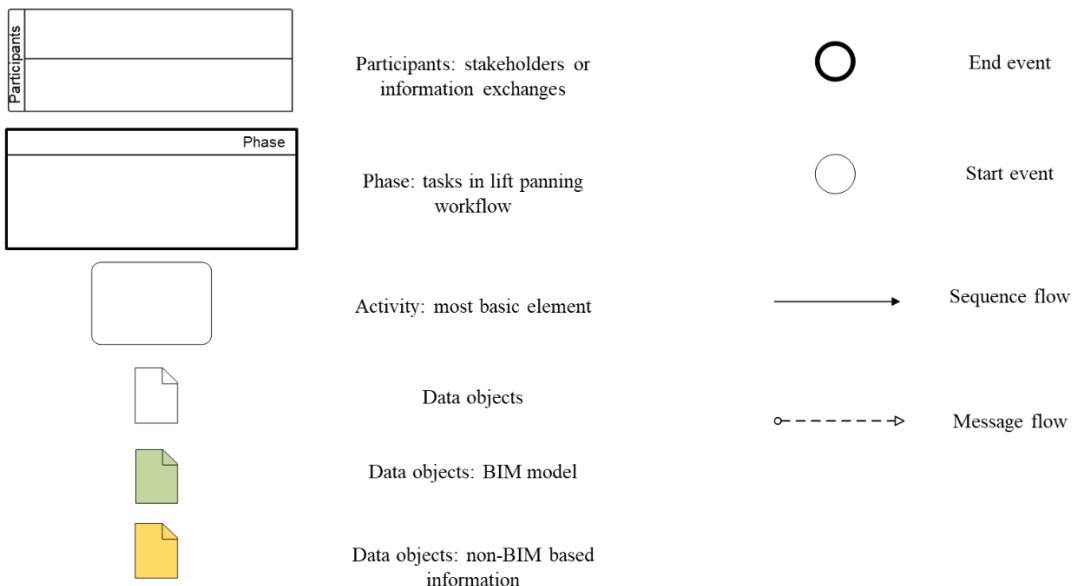


Figure 3 BPMN symbols and notations

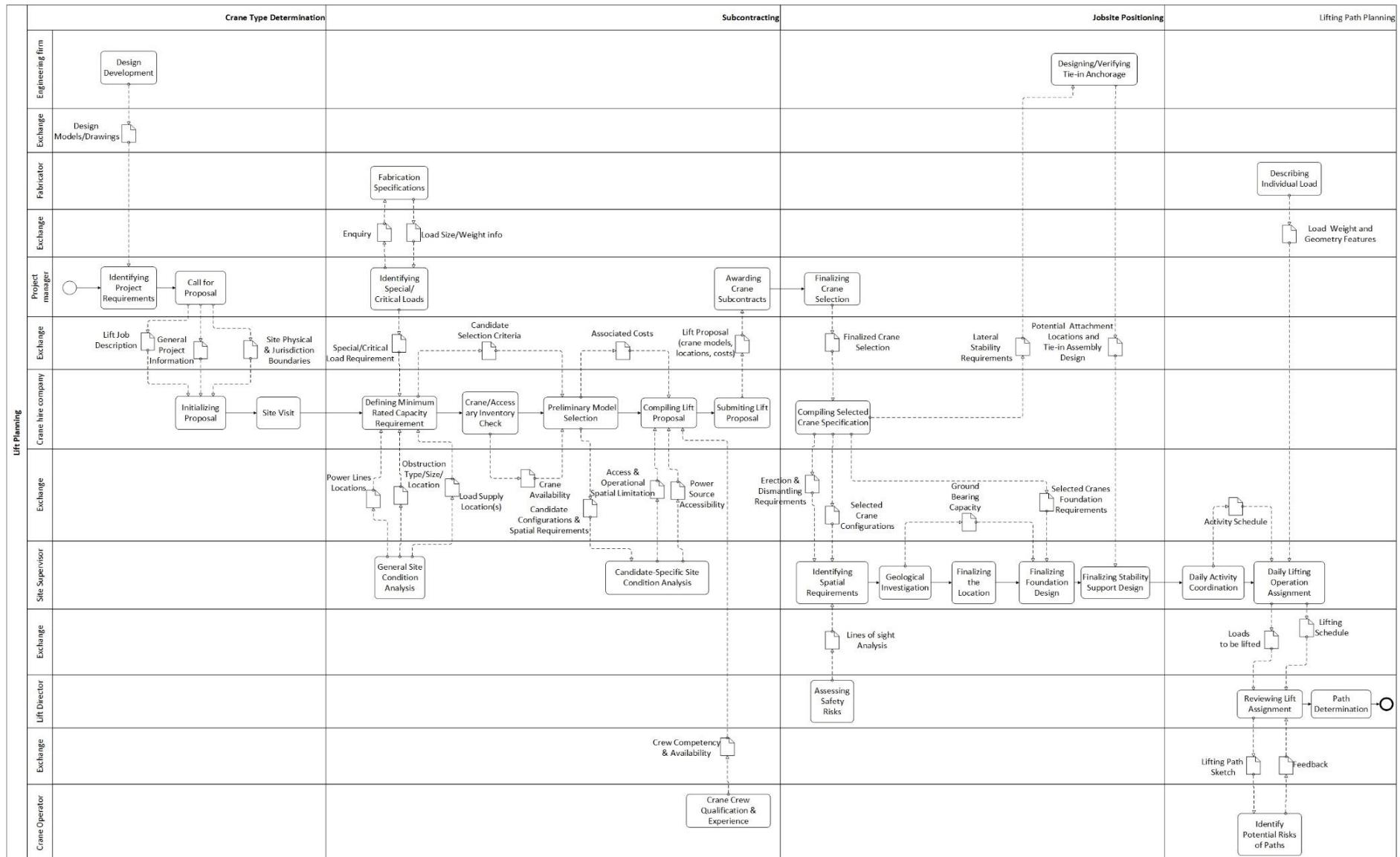


Figure 4 The BPMN model for traditional lift planning workflow

4.2. Reviewing the traditional workflow

Although the traditional crane lift planning workflow is widely adopted, potential improvements are distinctly identifiable. First of all, there is a mismatch between information and knowledge. From the information perspective, there are three clusters: building information, crane configurations, and site conditions. All three clusters of information are held by different stakeholders. For example, building information such as geometry and weight of building components is owned by the engineering firm; crane-related configurations such as jib length, free-standing height, load chart and availability are retained by the crane hire company; and site conditions are kept by site supervisors. In most cases, the decision-maker, who will use their knowledge, is not necessarily familiar with all the information. For example, the crane user determines the crane model but the model configurations are kept by the crane owner. Thus, the information has to be communicated between the information holder and the decision-maker. A decision maker has to request information, wait for information collectors to update their documents (e.g. drawings, paperwork or text files). Such a process occurs repetitively along the traditional workflow, introducing information ambiguity, loss and redundancy.

Additionally, the structure of the whole process is also bottlenecked by manual and experience-based decision-making. For example, the experience-based decision-making process lacks transparency and its result is neither optimal. Since the interests of all stakeholders do not always align, the interest of the project is not prioritized in some cases. For example, crane hire companies are likely to nominate cranes to reduce their inventory. Furthermore, as is discussed previously, the planning result is usually suboptimal due to time constraints.

The problems are partially resolved by applying emerging technologies, which not only enhance the comprehensiveness, timeliness and accuracy of information but advance the decision making. Nevertheless, their application is unsystematic, leading to new problems such as poor interoperability. Furthermore, these technologies have not changed the traditional workflow, which contains complicated and redundant information exchanges. These defects jointly refer to an urgent demand for an innovative lift planning workflow. Since the BIM is the foundation to integrate data acquisition technologies and automated decision-making, the innovative workflow is proposed within the framework of BIM.

4.3. BIM-based lift planning workflow

The BIM-based lift planning workflow synergized laser scanning, BIM and planning algorithms and proposed a novel BIM-based lift planning workflow. The workflow automatically manages information related to building, site, and crane equipment and search for optimal solutions with customized searching criteria. It starts when fabricators pass detailed coordination model to the general coordinator who will review the model and add in duration and budget information. Meanwhile, site condition is obtained via laser scanning, which is combined with the building information. Based on the combined model, planning algorithm estimates the minimum number of cranes needed for the project according to the total lifting demand and the minimum rated capacity for each crane via analysing the spatial relationship between supply area and demanding points. Then the capacity and coverage requirements are sent to the crane hire company for inventory checks. The crane hire company sends back a list of competent cranes specifying their configurations and quotations for candidate-specific investigation. Due to the variation of boom length and capacity chart, the feasible locations vary for each crane model. The planning algorithms can identify the feasible locations and enumerate the crane model and deployment location combinations. For each combination, the efficiency and safety indices are analysed to find the optimal combination of crane model and location. The planning algorithms further assist the stability designs such as base and tie-ins. When the above decisions are made, BIM visualizes the decisions for manual reviews. Finally, the results are elaborated in proposal awaiting approval from the project manager. Once approved, lift schedule and specific component information such as size, weight and hook locations take part in the determination of lift paths of each component, which is visualized and reviewed by the lift director and the crane operator before implementation.

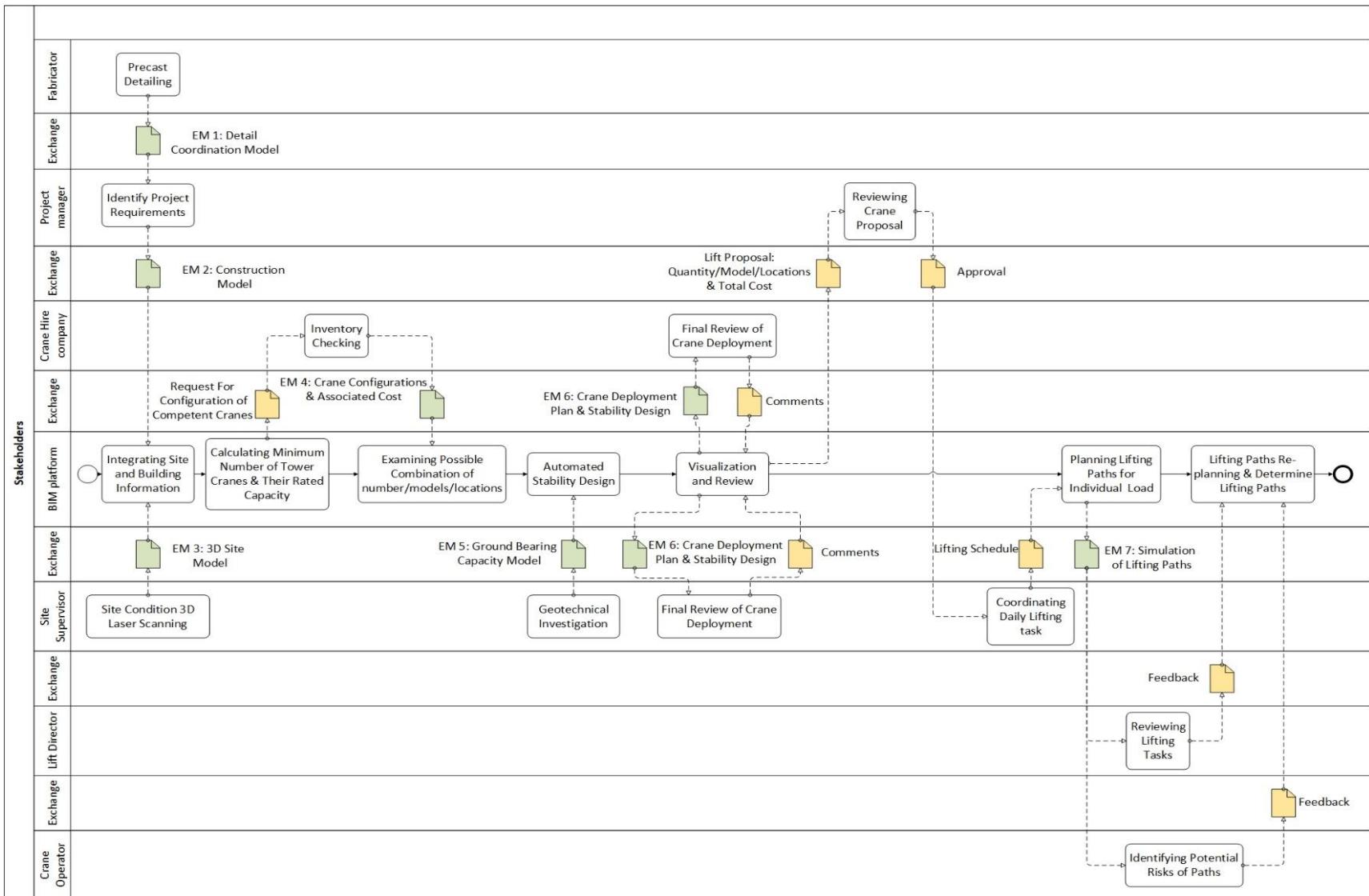


Figure 5 The BPMN model for the proposed lift planning workflow

5. DISCUSSION & CONCLUSION

Information technologies are reshaping AEC industry and creating more possibilities. However, previous efforts have mainly focused on the application of individual technology and neglected their impact on the workflow of lift planning. Thus, there is a demand to explore an innovative workflow organizing scattered technologies. This paper proposed such a workflow based on a thorough review of a validated traditional lift planning workflow. Both workflows are illustrated in BPMN process maps. It is expected that the newly proposed lift planning workflow is able to solve the limitations of the traditional workflow, such as redundant communications, information inaccuracy and decision-making opaqueness. By adopting the proposed workflow, site conditions, building information and crane configurations are synchronized to an integrated BIM-based information management environment. Therefore, the paper-based information exchanges are avoided together with the inherent ambiguity. Additionally, the automated decision-making for multiple tasks can be achieved simultaneously and there is no need to differentiate the tasks and their responsible stakeholders, reducing the complexity of information exchanges. Furthermore, the system is expected to enhance the transparency of decision-making. For example, the project management team retains the privilege of finding the most economical tower crane without interfering in other considerations.

Despite the foreseeable advantages, the limitation of this study is its application scope. Since the interviews targeted at the crane industry practitioners in Australia, the traditional workflow only reflects the practices in Australia. Additionally, several barriers and topics for further research still exist.

- Firstly, existing BIM platforms cannot satisfactorily support all the necessary information for the planning algorithms. For example, the current information model such as IFC does not have sufficient items for crane configurations and costs. Hence, there is a demand for expansion of the BIM data schema for lift planning;
- Secondly, most research on planning algorithms has hitherto focused on individual tasks. Thus, the same information has to be repeatedly retrieved, weakening the efficiency of the new workflow. Therefore, an integrated lift planning algorithm is needed;
- Thirdly, the interoperability of technologies can be challenging when implementing the innovative workflow. Typically, it takes a team of professional personnel to ensure that every stakeholder can understand the information generated by different types of technologies. However, the extra costs are anticipated to discourage contractors. Thus, there is a lack of unified information schema or a common protocol, enhancing their interoperability.

In conclusion, the study investigated the impacts of cutting-edge technologies on the lift planning workflow and underlined the missing pieces to support a federated, integrated lift planning system. Furthermore, this paper also identified the existing challenges for implementing the new workflow, which exhibits the initial steps to achieve the proposed workflow.

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3D Printing in Modular Construction: Opportunities and Challenges

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Abstract: Modular construction is a construction method whereby prefabricated volumetric units are produced in a factory and are installed on site to form a building block. The construction productivity can be substantially improved by the manufacturing and assembly of standardized modular units. 3D printing is a computer-controlled fabrication method first adopted in the manufacturing industry and was utilized for the automated construction of small-scale houses in recent years. Implementing 3D printing in the fabrication of modular units brings huge benefits to modular construction, including increased customization, lower material waste, and reduced labor work. Such implementation also benefits the large-scale and wider adoption of 3D printing in engineering practice. However, a critical issue for 3D printed modules is the loading capacity, particularly in response to horizontal forces like wind load, which requires a deeper understanding of the building structure behavior and the design of load-bearing modules. Therefore, this paper presents the state-of-the-art literature concerning recent achievement in 3D printing for buildings, followed by discussion on the opportunities and challenges for examining 3D printing in modular construction. Promising 3D printing techniques are critically reviewed and discussed with regard to their advantages and limitations in construction. The appropriate structural form needs to be determined at the design stage, taking into consideration the overall building structural behavior, site environmental conditions (e.g., wind), and load-carrying capacity of the 3D printed modules. Detailed finite element modelling of the entire modular buildings needs to be conducted to verify the structural performance, considering the code-stipulated lateral drift, strength criteria, and other design requirements. Moreover, integration of building information modelling (BIM) method is beneficial for generating the material and geometric details of the 3D printed modules, which can then be utilized for the fabrication.

Key words: 3D printing, building information modeling, geometry optimization, modular construction, structural connection

1. INTRODUCTION

The construction industry is now confronted with some great challenges like skilled labor force shortages, cost escalation and environmental constraints. Different solutions to address these challenges have been explored in recent decades, including modular construction and 3D printing using concrete. Modular construction is a construction method whereby prefabricated volumetric units are produced and fitted-out in a factory and assembled on the construction site to form a building block. This approach has been introduced and promoted to the industry worldwide, and is proven to be capable of substantially shortening the on-site construction period, improving health and safety of site staff, enhancing construction quality and minimizing the construction waste. 3D printing is a computer-controlled fabrication method first adopted in the manufacturing industry and was utilized for automated construction of small-scale houses in recent years. For the Architecture, engineering, and construction (AEC) industry, 3D printing techniques using

different materials including concrete, wood and resin have been explored, though this paper mainly focuses on printing processes using concrete.

3D printing and modular construction complement each other perfectly. On one hand, though modules are manufactured in a factory, formwork is still required in the case of the concrete modules, which places restrictions on module customization/optimization and requires a considerable amount of time and materials for production. 3D printing provides modular construction with a viable solution for getting rid of formwork design, production and erection, by directly building up the designed objects. On the other hand, 3D printing has generic criticism that the scale of the printed object is restricted by the printer's size. For modular construction wherein standardized modules are usually designed as room-sized repeated units to meet the requirements of transportation and assembly, as it is considered more suitable for the adoption of 3D printing. In this paper, the state-of-the-art literature on recent achievements in 3D printing of buildings or components is presented, together with the possibilities and challenges for adopting 3D printing in modular construction. Promising 3D printing processes are critically reviewed and discussed in terms of their main features in practice. A framework for 3D printing implementation in modular construction is proposed and some steps of the framework are further discussed.

2. OVERVIEW OF CONCRETE 3D PRINTING

2.1. Available 3D Printing Techniques

3D printing, which is also referred to as additive manufacturing (AM), is a computer-controlled fabrication process to transform a digital model into a 3D solid object. Generally, in a 3D printing process, the digital model of the object (often in STL format), is sliced into a series of 2D layers using a specific algorithm and is constructed layer by layer. According to ASTM and ISO [1], existing 3D printing processes are classified into seven generic categories according to the technology used to construct the layers, as shown in Table 1. These include the most common material extrusion and powder bed fusion processes (widely adopted in metal printing). The material extrusion process is also widely adopted in the building and construction (B&C) industry, and is a kind of AM process whereby material is selectively dispensed through a nozzle or orifice according to the pattern of object's 2D layer.

Table 1. Seven categories of 3D printing processes [1]

Categories	Definition
binder jetting	A liquid binder is selectively deposited into a bed of powder materials.
directed energy deposition	Material is melted by focused thermal energy when being deposited.
material extrusion	Material is drawn through a nozzle and selectively deposited.
material jetting	Droplets of material are selectively jetted onto the build surface or platform.
powder bed fusion	Selective regions of a material powder bed are fused by thermal energy.
sheet lamination	Sheets of material are cut according to the required shape and bonded together.
vat photopolymerization	Liquid photopolymer is selectively cured by light-activated polymerization.

Nowadays, concrete is still the most widely used and publicly accepted construction material worldwide because of its high compression strength, relatively low cost, fire resistant and easy shaping. However, the traditional manufacturing methods also have some drawbacks, which is gaining more attention as the B&C industry is putting more emphasis on construction safety, sustainability and effectiveness. For in-situ reinforced concrete structures, demanding physical labor is required particularly for the erection of formwork and the placement of reinforcements, whereas the formwork is not always reused, and put constrains on mass customization and geometrical optimization. 3D printing of concrete provides a promising solution to address the above drawbacks. Since formwork is not needed in 3D printing, manufacturing special-shape and customized elements is available at no extra cost, which break down the barriers, giving more design freedom. It also offers potential of building in additional functionality and construction automation, reducing the physical labor involved in the manufacturing procedure. In addition, 3D printing of concrete is found to reduce the carbon emissions in the whole manufacturing stage.

2.2. Concrete 3D Printing

Depending on the technologies used in 3D concrete printing processes, most variants of this family are categorized into material extrusion methods including Contour Crafting and Concrete Printing, with the exception of D-shape, which is a kind of binder jetting method. (as shown in Figure 1). Contour Crafting (CC) was first introduced to the B&C industry by Khoshnevis [2] at the University of Southern California as an innovative rapid prototyping process to make large sized complex shapes with smooth surfaced. It is an extrusion-based process stacking concrete-like extrudate onto lower layer. Two trowels are used in this process and serve as solid plane surfaces, allowing the smooth surfaces of the object to be accurately printed [3]. Some preliminary projects were finished by Shanghai-based contractor Winsun, and the company Total Kustom in Minnesota, USA.

Concrete Printing (CP) is another extrusion-based 3DCP process, developed by a research group of the University of Loughborough, UK [4]. This process is quite similar with CC, but has a smaller printing features of deposition (or resolution), which allows for better control of the printed object's geometry. A practical example to illustrate the design and manufacture of a concrete component called Wonder Bench, was provided by Lim et al. [5], which also demonstrated a suitable reinforcement strategy for printing large components.

Dini [6] developed and exhibited the D-shape process at the Civils 2007 exhibition at Earls Court in London. This process is a kind of binder jetting method, selectively depositing a liquid binder on top of layers that bonds the material powder (dry-mixed sand and magnesia cement) to produce the object. It allows designs to have voids and overhanging features, enabling the printing of complex geometries, which is not that practical or is impossible for other 3DCP processes. However, this particularity also leads to the need for removal of large amounts of unbound material powders. Therefore, the technology is more suitable and mainly used for the off-site manufacture of unique parts such as custom concrete-like sculptures, rather than conventional buildings. The technology has been used in numerous projects including a printed bridge in Madrid, Spain and a 3D printed reconstruction of Palmyra's Arch of Triumph. Universe Architecture and contractor BAM are using the D-Shape technique to develop the Landscape House in Amsterdam, the Netherlands [6].



Figure 1. Three typical kinds of concrete 3D printing technologies: (a) Contour Crafting [3], (b) Concrete Printing [5], and (c) D-shape [6]



Figure 2. Elements printed by (a) Contour Crafting [7], (b) Concrete Printing [8] and (c) D-shape [6] respectively

These three technologies have different printing resolutions. The resolutions of material extrusion methods are constrained by the section of the filament, and the later-developed CP process has a smaller resolution than CC. The D-Shape is supposed to have smallest resolution of these three processes, since using material powder allows a minimal distance between layers. But the fact is that the accuracy of the D-

Shape technique was reported to be hard to control because of the spreading of the liquid binder through the powder mix. The quality of the printed elements of the three technologies can be seen in Figure 2.

Because the printing processes are formwork-free and require a high degree of control and early-form stability, material extrusion methods normally operate fine aggregate mixes (usually without coarse aggregates) with low water-cement ratio and of low slump and fast setting, which is quite different from the traditional way. Research on 3D printable materials is reviewed by Suvash [9], including material composition, rheological properties (pumpability, extrudability and buildability) and mechanical properties (compressive and flexural strength, inter-layer bond strength and drying shrinkage). How the material properties influence the parameter settings and printing quality is discussed in next section. For D-Shape, magnesia cement is used, creating concretes with far superior mechanical properties compared to traditional Portland cement, but some crucial drawbacks exist, such as poor water resistance, prone to shrinkage, expansion, cracking and warping, and highly unpredictable bulking behavior.

2.3. Types of Concrete 3D Printers

A 3DCP system usually consist of a movement system, a deposition system and material feeding system. The moving system allows the deposition head to move in 3D space and it can be categorized into two kinds, namely: Cartesian and Delta. The Cartesian printer function based on the Cartesian coordinate system and the print head travels linearly on each axis to deposit the filament, while in the Delta printer the print head navigates and is located directly within the 3D print space. The deposition system normally refers to the nozzle(s), and in CC it also includes trowels to create the smooth outer and top surfaces of a layer, while in D-Shape it is made of a series of nozzles placed in a straight line along a beam. The material feeding system for material extrusion processes includes equipment to mix the materials, pump and deliver the composite to a hopper on the top of the deposition head, while for D-shape, two components need to be delivered to the printer: the liquid and the dry powder mix.

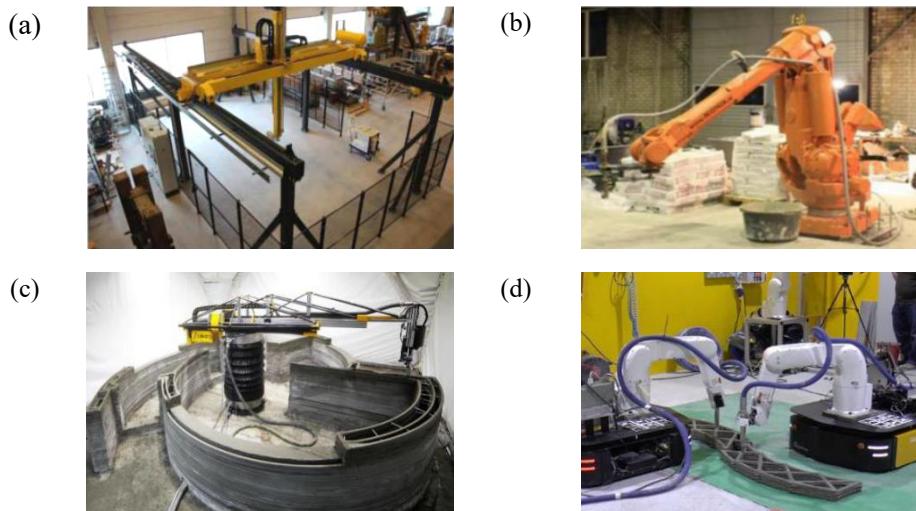


Figure 3. Current 3D concrete printers, (a) four-axis gantry printer [9], (b) six-axis robotic printer [9], (c) crane printer [12] and (d) a team of robots [10]

A gantry robot with 3 or 4 degrees of freedom (DOF) (as shown in Figure 3(a)) and articulated robots with 6 or more DOF (as shown in Figure 3(b)) are most widely used. The former is mainly used in large projects, while the latter is generally adopted to produce smaller objects. Crane systems (as shown in Figure 3(c)) have also been successfully adopted in industry and universities. Gantry and crane printers have the superiority of being easy to scale in size and lower cost. In contrast, the sizes of robots are typically fixed, leading to difficulty in scaling up of this kind of printers. However, the advantages of using a six-axis robot or robot arm is that its speed and degrees of freedom allows more printing tasks with more complexity to be finished per unit time, compared to a four-axis gantry printer [9].

A replacement to printing with single, large robots was proposed by the Singapore Centre for 3D Printing of Nanyang Technological University – multiple mobile robots printing concurrently using localization and

path planning technology working together, as shown in Figure 3(d) [10]. Minibuilders using resin material are also described in detail by Nan et.al. [11], and were proven to be lightweight, compact and have autonomous mobility.

2.4. Main Features of 3D Printing Processes

Compared with conventional 3D printing processes, 3DCP has some prominent features that are worth consideration. These features mostly result from the material used and sheer size of the printed object. Materials used in all 3DCP, usually mortar or cement with special composition, solidify through a curing process, which is much slower than that in conventional processes and results in the pre-setting status of the object during the printing procedure. Some conventional 3D printing techniques also utilize heat or UV to accelerate the material hardening. For material extrusion methods, the section area of filament in 3DCP is hundreds or thousands of times larger than that in conventional processes, requiring extra consideration in printing procedures [9].

Parameter sensitivity: The parameter sensitivity issue is one of the consequences resulting from the pre-setting status of the printing material. Since the solidification time is much longer, the parameters in printing setting including print head speed, pump frequency, material properties and time interval between layers, have a significant effect on the quality of the printed object. The nozzle type also has significant effect on the buildability of 3DCP. For example, by using a circular nozzle orifice instead of a square orifice, the contact area between successive layers can be extended, increasing the inter-layer adhesion [13].

Geometrical confinement: There are more geometrical confinements in 3DCP. In traditional processes, when the printing object has an over-hanging part, a support is created by the build material or a second removable material. In the cases of binder jetting and other powder-based processes, the self-weight is supported by the unsolidified material powder, which allows having full three-dimensional printing freedom. For the extrusion-based method, overhang features can be produced by building up a support with a removable material or using corbeling, but these two strategies have their own drawbacks – an additional deposition device is required which needs more maintenance, cleaning and control instructions, and extra labor and difficulties in erecting corbeling. In addition, premature collapse should be taken into consideration in the printing. For material extrusion processes, when corners are introduced in the printing, there will be a difference in deposition rate between the inside and the outside of the filament, which leads to material inconsistency. To avoid cracking in filaments, the radius of curvature should be larger than a specific minimum value.

With parameter sensitivity in the printing setting and geometrical confinements of the printed object, 3DCP puts more emphasis on the integration of design and manufacturing. Besides, preparation of the printed model in 3DCP requires a different algorithm from that in conventional processes in order to slice the digital model and generate the printing path.

3. CHALLENGES FOR 3D PRINTING IN MODULAR CONSTRUCTION

3.1. BIM-based framework for modular construction using 3D printing

Building information modeling (BIM), as the digital expression of a construction project's physical and functional characteristics, it is widely used in the construction of prefabricated buildings home and abroad [14]. 3D printing as a computer-controlled manufacturing method, requires a digital model of the printed object and instruction on the printing path. It is widely accepted that for 3DCP, the stage of design should not be isolated from the printing procedure as it has a significant effect on the quality of the printed product. By combining BIM and 3D printing in modular construction, the geometrical and other semantic information such as materials, equipment, resource and manufacturing data, stored in the BIM model can be easily used for the production and installation of customized building components. Figure 4 offers a framework for BIM adoption in 3D printing for modular construction.

Building design: Firstly, the architect assembles a customized floor plan using a library of units according to the building layout. Afterwards, a structural engineer is engaged and establishes a structural model for analysis, while the MEP design group makes use of a library of MEP modules to design the building service systems [14].

Module design: Parametric design is then carried out on the printing component or module as a 3D model in the BIM software (like Revit). It is advised to undergo an optimization process for the layer pattern and topology distribution to remove unnecessary material, with consideration of the geometrical constraints and the optimization of the printing procedure. Then the optimized model is converted to STL (Standard Template Library) file format, sliced with a desired layer depth, after which a printing path for each layer is generated and a G-Code file is created for printing. Since currently no family for 3D printing components is available in BIM software like Revit, the authors suggest that some plug-ins like Dynamo in Revit can be used for convenience to extract data from the BIM model and carry out module prototyping and optimization. The process can also take advantage of families being further developed.

Fabrication and assembly: Modules can be produced according to the fabrication schedule generated from the BIM model and then transported to the construction site and assembled. The BIM model could also be used for tolerance control of the 3D printing components and overall assembly. Though it makes little sense for a single module since a CAD model and the printed object have different textures and consequently comparison between them could not provide meaningful evaluation of the manufacturing accuracy (a CAD model generally has smooth surface while printed object has a stepped surface) [4]. However, a BIM model together with other hardware, such as total station, could be used to inform construction managers on the assembly tolerance so as to avoid large eccentricity, reducing resulting additional moment.

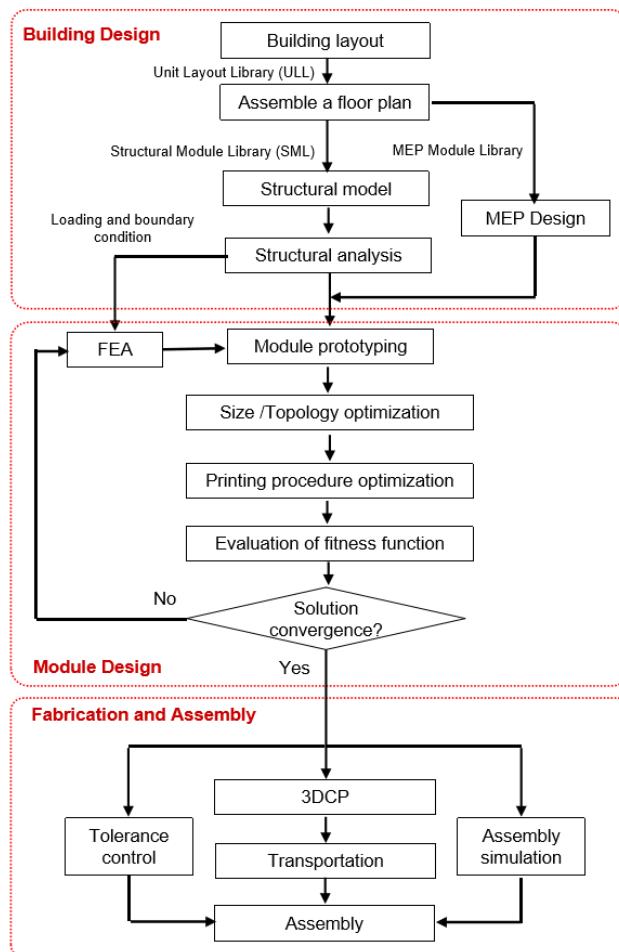


Figure 4. Framework for 3D printing adoption in modular construction

3.2. Structural design for entire modular buildings

Some strategies to provide stability and robustness have been proposed to extend the modular construction method to high-rise buildings [15]. A structural system with one or several concrete cores, as shown in Figure 5, is widely used, in which modules are designed to resist compression and the core

provides overall stability. Modules are either clustered around a core without a separate structure or connected to in-plane trusses placed within the corridors. In the formal case, the horizontal load is directly transferred to the concrete core, while in the latter case, the horizontal load is first transferred to the trusses and then to the core. An alternative to this system is to design a ‘podium’ or platform structure on which the modules are placed. In these structural systems, the module units are mainly subjected to compression force. For 3D printing modules, the inter-layer shear capacity is relatively lower due to the layer-by-layer manufacturing process and the difficulty of adding reinforcements in the printed object. Therefore, in terms of mechanical properties, these kinds of systems are suitable for adopting 3D printing in module prefabrication.

Structural systems that are widely used in commercial high-rise buildings seem to correspond with the concept of using a concrete core to resist horizontal force, like the core and outrigger structural system. Modular buildings are mainly adopted in buildings having standardized units such as residential units, hotels and dormitories, which usually require a higher degree of design freedom to meet functional requirements. Therefore, those structural forms with regular layout may not be suitable for modular construction, even though some parts of these types of buildings can be fabricated and assembled on site. Very few research works mentioned how to carry out structural analysis on modular buildings, especially for concrete modules. For example, Alawneh et al. carried out finite element analysis on a 3D printed and assembled concrete structure [16]. However, the calculation model and assumption for such analysis are not clear.

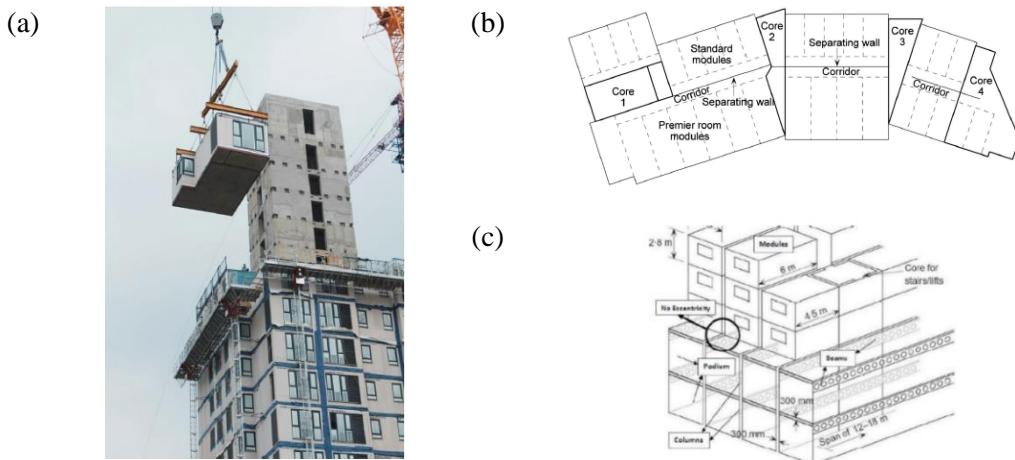


Figure 5. Some typical structure systems of modular building: (a) concrete core [17], (b) braced cores [15] and (c) podium structure [15].

3.3. Geometry design and optimization for 3D printed modules

Since objects are usually not printed in solid form in 3DCP, an additional post-processing step is required on the BIM model to prepare the data for printing. Clash detection, geometrical confinement and constructability analysis should also be taken into consideration during this prefabrication stage. Figure 6 illustrates the concept of module prototyping and manufacturing, including a procedure using Dynamo in Revit to generate the section pattern of a structural wall, in which a sine curve is used as the middle layer. Note that any customized pattern is also allowed since formwork-free 3DCP does not have extra difficulties in creating elements with different sections. Finite element analysis (FEA) on specific elements can also be carried out using the loading extracted from the structural analysis, and optimization of the geometrical pattern of each layer can be carried out based on the FEA results.

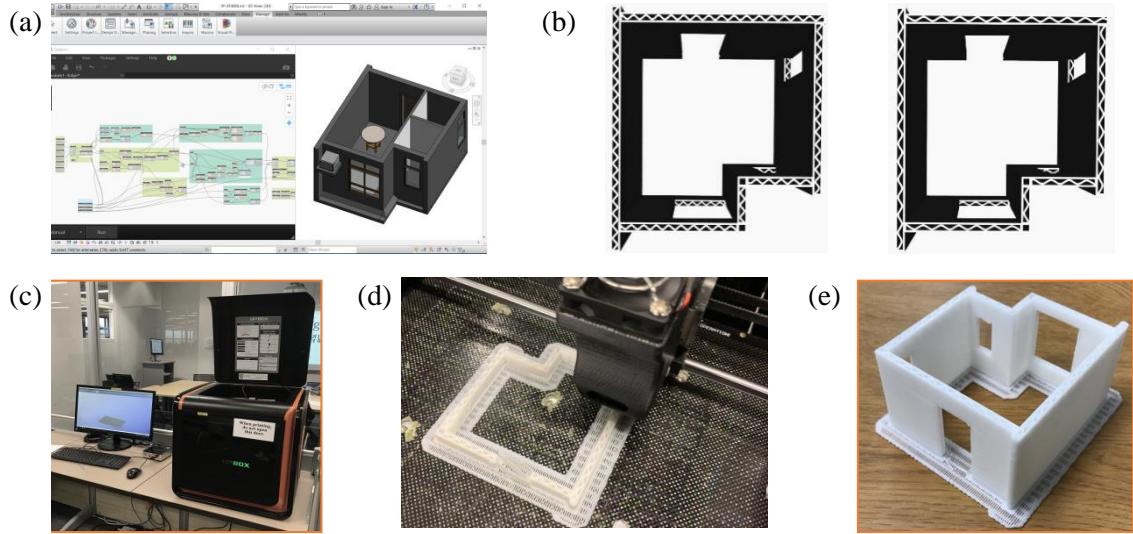


Figure 6. Conceptual illustration of module prototyping and manufacturing including (a) parametric model in Dynamo, (b) optimization, (c) STL file for 3D printing, (d) manufacturing using material extrusion process and (e) finishing.

3DCP requires a different algorithm to slice the model and generate the printing path from those used in other AM processes. As previously mentioned, printing parameters have great influence on concrete printing, and may result in catastrophic failure if inappropriately selected. In material extrusion processes, the flow rate should properly match with the print head speed to avoid inconsistency in the layer thickness. In addition, the time interval between layers should be controlled in an appropriate range according to the material properties, in order to ensure the adhesion between layers. Therefore, optimization is necessary for the printing path of the deposition head to avoid material over-print, minimize the non-printing movements of the deposition head and improve the printing quality, while considering flow rate, print head speed, material properties and et al. as input variables.

3.4. Module manufacture and installation: reinforcement

Concrete is material with low tensile strength and ductility. In conventional construction, reinforcements or post-tensioning steels are generally added to the concrete to for better structural performance and structural reliability. However, in 3DCP, the addition of concrete is not that straight forward. Post-tensioning reinforcement and imbedded reinforcements or steel mesh on intermediate layers [Figure 7 (a) and (b) respectively] are used in some projects, such as the office building in Dubai [16]. However, so far these methods are carried out manually. To achieve the potential benefits of construction automation, the process of placement of the reinforcements in different directions should be fully automated. Steel modular components [Figure 7 (c)] were proposed by the inventor of Contour Crafting for automated reinforcement [3]. Van Zijl et al. provided a solution for the extrusion of strain-hardening cement-based composites (SHCC) with steel bars [18], as shown in Figure 7 (d). In this case, steel bars are entered horizontally and drawn automatically through special openings. Bos et al. developed a device to directly entrain a reinforcement medium into the filament of the printed concrete, as shown in Figure 7 (e) [19]. In this method, wire reinforcements with high flexibility are used, allowing the print head movement in 3D space, like turning a curve or rise from the lower layer to the next. Using composite fibre mixed into printing filament is another adjustment 3DCP technology, which has been found effective for improving the structural capacity and ductility of concrete objects [20]. Researchers in Singapore Centre for 3D Printing offered an innovative approach, in which steel fibres are automatically injected into an existing layer by a robot before the next layer is deposited, as shown in Figure 7 (f), though the approach is still at a preliminary stage and requires much research work for successful adoption [9].

Nevertheless, most solutions discussed above, placed reinforcements on intermediate layers or between the filament layers, which had little effect on improving the shear capacity of the layer interface. Therefore, vertical reinforcements are necessary and much benefit in regard to structural integrity would be gained, but practical difficulties exist because vertical reinforcements may block the movement of deposition head.

Manual placement of reinforcements [Figure 8(a) and 8(b)] has been adopted as a simple workable method in some projects, such as a 6-story apartment building printed by Shanghai-based WinSun 3D [21]. In this approach, reinforcements are placed in the space between the filaments, and the voids are further grouted to ensure the integrity of the reinforcements and printing parts. Direct deposition of concrete on the side of the manually pre-tied reinforcement cage is also used in some cases [22] [Figure 8(c)], but it seems the method has poor applicability when the size of reinforcement cage becomes larger.

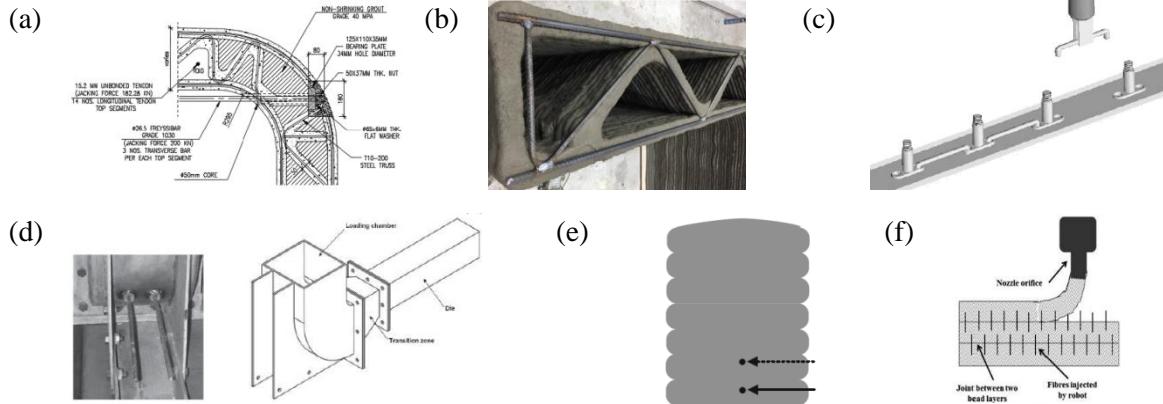


Figure 7. Strategies to install reinforcements in printing objects: (a) post-tensioning steels [13], (b) imbedded reinforcements [13], (c) steel modular components [3], (d) extrusion of composites with steel bars [18], (e) extrusion of filaments with steel wires [19] and (f) automated injection of steel fibres [9].

As discussed above, reinforcement installation using different arrangements is practical in the 3D printing module, and the connections between the modules and those between the modules and the main structure could be further established. The prefabrication industry has developed rapidly in recent decades in mainland China, and also offers some methods for reinforcement connection for modular construction. It could be found from Figure 8 (b) that sleeve connections have already been adopted in reinforcement connection in 3DCP. Some experiments conducted on prefabricated components or structures using specific connecting techniques could also provide evidence for the assumptions used for connections in structural analysis.

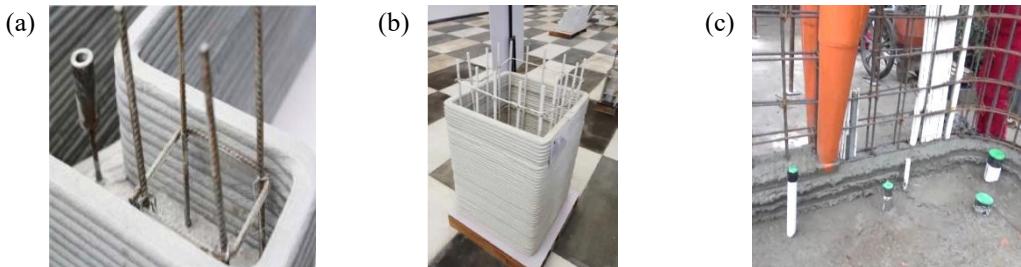


Figure 8. Application of vertical reinforcements in 3DCP. (a) (b) Manual placement of reinforcements [9, 21] and (c) direct deposition of concrete on the side of pre-tied reinforcement cage [22].

4. CONCLUSIONS

Adopting 3D printing in concrete modular buildings is a new concept, but one that can take advantage of prefabrication and computer-controlled manufacturing. In this paper, existing 3D printing processes are reviewed and three typical 3D concrete printing processes are discussed from the perspective of the characteristics and system components. It is found that 3DCP has distinct features such as parameter sensitivity and more geometrical confinement compared with conventional processes, which should be taken into consideration in module building design. A BIM-based framework is also proposed to illustrate how these techniques can be integrated to gain higher productivity. Some aspects in this framework are further discussed and some workable solutions are provided, including selection of the modular building

structural system, module prototyping and optimization and reinforcement installation. In some procedures, challenges still exist, and elimination of them would allow full automation of the printing process, with the benefits of better accuracy control, higher productivity and reduced material waste.

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IV. RISK AND SAFETY MANAGEMENT IN CONSTRUCTION I (B1)

Correlation Extraction from KOSHA to enable the Development of Computer Vision based Risks Recognition System

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Abstract: Generally, occupational safety and particularly construction safety is an intricate phenomenon. Industry professionals have devoted vital attention to enforcing Occupational Safety and Health (OHS) from the last three decades to enhance safety management in construction. Despite the efforts of the safety professionals and government agencies, current safety management still relies on manual inspections which are infrequent, time-consuming and prone to error. Extensive research has been carried out to deal with high fatality rates confronting by the construction industry. Sensor systems, visualization-based technologies, and tracking techniques have been deployed by researchers in the last decade. Recently in the construction industry, computer vision has attracted significant attention worldwide. However, the literature revealed the narrow scope of the computer vision technology for safety management, hence, broad scope research for safety monitoring is desired to attain a complete automatic job site monitoring. With this regard, the development of a broader scope computer vision-based risk recognition system for correlation detection between the construction entities is inevitable. For this purpose, a detailed analysis has been conducted and related rules which depict the correlations (positive and negative) between the construction entities were extracted. Deep learning supported Mask R-CNN algorithm is applied to train the model. As proof of concept, a prototype is developed based on real scenarios. The proposed approach is expected to enhance the effectiveness of safety inspection and reduce the encountered burden on safety managers. It is anticipated that this approach may enable a reduction in injuries and fatalities by implementing the exact relevant safety rules and will contribute to enhance the overall safety management and monitoring performance.

Keywords: KOSHA rules, computer vision, objects correlation, risk recognition, safety inspection

1. INTRODUCTION

A safe environment is mandatory in all industries, while in construction, it is of particular importance because of the fourth highest fatal injury rates among all industries [1]. The construction industry reports show the incident rate of 36% in Singapore, 29.3% and 27% in South Korea and UK respectively, which is approaching to double than other industrial averages [2], [3]. Strong enforcement of safety regulations is a vital way to enhance construction safety and minimize accidents. Moreover, these safety regulations play a basic role in construction risk identification in the pre-construction and during construction.

Onsite safety monitoring is pivotal as it is the last safety management layer to prevent accidents. Since accidents happen during the physical construction work, so, extensive exertions had been given to enhance the effectiveness of inspection on job site during work. Unfortunately, current construction safety monitoring still relies on manual inspections, which are expensive and not always possible, thus, need to be improved and ultimately automated. In recent years, several approaches and techniques based on safety regulations, accident cases, training, and education have attempted new ways to enhance safety management. Among various methods to manage effective construction safety, application of advanced techniques such as computer vision, machine learning, blockchain, smart sensors, motion tracking technologies, augmented reality holds huge potential for proactive prevention of accidents and automatic risk identification.

Considering the recent construction context, computer vision and machine learning hold the ginormous potential to enhance the efficiency of the various tasks in construction safety monitoring, progress checking, defect detection and so on. The unprecedented increase in the visual data from the job site enables a unique opportunity for computer vision systems to be deployed widely which could improve safety performance and safety monitoring [4]. For instance, absence of helmet, wrong position or absence of fire extinguishers, absence of guardrails at the edges of excavation and floors, are handled with object detection systems. Also, object trackers systems or action recognizers are used to detect dynamic hazards such as moving equipment and workers. However, far as the scope and application of existing systems are still limited, thereby mostly consider some specific activities, equipment, worker behavior, and hazard types.

To eradicate potential hazards at the right time, continuous job site monitoring is required for unsafe acts. The unsafe acts include actions such as, but not limited to, positive and negative relationships between the construction entities which could be a direct reason for the accident. For instance, considering welding activity: fire extinguisher with welding machine, gloves and safety glasses (helmet) with the person shows a positive correlation. The example of a negative correlation could be the relation between electric wire and water, use of a ladder on scaffolding and many more. To fill the gap, this paper envisions to enhance construction site safety monitoring by introducing a safety rule compliance computer vision-based correlation recognition system with a larger scope. Deep learning supported computer vision technology is considered a feasible solution due to high performance, simple structure, and cost-effectiveness, as most of the construction job sites are currently equipped with the CCTVs. Rather than the traditional safety monitoring process whereby safety manager inspects the safety rule compliance in Jobsite physically, computer vision-based job site safety monitoring provides a reliable approach which allows automatic recognition of objects, hazards, and unsafe behavior.

2. LITERATURE REVIEW

2.1. Current Safety Monitoring Status

Generally, the construction sector and its clients are widely linked with high risks due to the nature of micro, meso and macro environments specific to the construction [4], unfortunately, due to ineffective dealing with that unique hazardous environment, construction industry has not a good reputation globally. The standard current practice to deal with the safety hazards in construction involved monitoring of job site environment. In order to identify any potential hazard or safety rule incompliance during construction, the safety manager must be present physically. The success of these physical visits for safety compliance depends on the experience and competence of the safety manager. In addition, existing inspection methods are painstaking and time-consuming [5]. In the recent decade, researchers have focused on enhancing the safety management process by using new technologies. Generally, the safety management process includes safety planning in the pre-construction stage and safety monitoring during construction stage. Many researchers proposed an advanced safety planning process by extracting relevant safety rules from the regulation database and then integrating that domain-specific rules with Building Information Modeling BIM [6], [7]. BIM is also utilized for hazard location detection in safety monitoring stage by several researchers which reduces cost and time. However, this approach still needs a manual inspection for generating safety reports from the field. In fact, researchers have recently introduced vision-based automated safety monitoring during construction which can minimize the existing problems in manual safety inspection [5], [8]–[10]

2.2. Computer Vision (CV) based Technologies in Construction

Unlike other industries such as manufacturing industries, the construction industry comprises a complex working environment and sometimes non-standardized operating procedures. Consequently, this unique nature creates challenges for safety monitoring and occupation health. Computer vision-based technology has been adopted in various areas of construction such as hazard recognition, defect detection, progress monitoring, productivity analysis, and automated documentation. Recent research in vision-based monitoring of the construction sites has focused on the development of the simple inspection system for the detection of basic hazards, for example, hard hats detection [11] and safety harness recognition for fall hazard [9]. Resources detection such as human resources, materials, and machinery/equipment is another development in the same domain which has been made in the near past [12]–[14]. Nevertheless, the “objects” detection ability of the trained models in these research studies is noticed limited. One reason could be the limited dataset used to train the models. Many researchers have focused on exploiting descriptors for machine learning classifier and only a few have explored the neural networks application for object detection in construction. In this paper, a science of design research methodology was adopted [15] to develop a risk detection system by employing neural networks algorithm that could be used to automatically recognize positive and negative correlation among the objects.

3. CORRELATION EXTRACTION FROM KOSHA REGULATIONS

In 1953, labor standard law led the foundation for industrial safety and health policy in Korea. Thereafter in 1987, Korea Occupational Safety and Health Agency (KOSHA) was established with regards to the rapid development of industries in 1970 to 180. The related acts were revised in order to meet the mandatory demand for safety and health standards required for various industries having a toxic and complex environment. Since then KOSHA collected and analyzed many accident cases, thereby resulted in the expert knowledge database. Based on that, Substantial amendments have been made to ameliorate the past polices for modern industry compliance and global competition.

The vital point to consider is that despite strong enforcement of occupational safety regulation and expert knowledge around the globe, the construction safety management process still relies on traditional practices. Computer vision can enhance the construction safety enforcement and implementation process, thus, by converting the expert knowledge, in this case, the rules into practicality by using deep learning algorithms. Therefore, the KOSHA regulations were analyzed and relevant rules having relationship information, either positive or negative were extracted. The KOSHA regulations standards on occupational safety and health are manually investigated by the authors manually at a basic clauses level.

Table 1. Analysis of KOSHA Regulations

Description of Construction Related Articles from KOSHA	No of Articles	Percentage (%)	Technology Application	
Correlation between the resources explained by articles	305	36.90	Computer Vision	
Limited access zone and numerical related articles	171	20.70	Computer Vision	
Miscellaneous articles	106	12.80	ICT excluding Computer Vision	
Remaining articles	245	29.6	Unable to be covered using technologies	
Total	824	100	Computer Vision	Others
			57.60 %	42.40 %

The KOSHA regulations consist of 13 chapters which include various sections followed by 671 standards, out of which 277 are related to the construction sector. These 277 standards further contained clauses that were thoroughly investigated and classified. The first step was to determine the standards which reflect the construction industry and then the potential of computer vision adoption was examined on the extracted standards. Subsequently, the object relationships based on the correlation, whether positive (+) correlation (objects relation is compatible with each other) or either negative (-) correlation (objects relation is not compatible with each other) within the articles were studied.

The analysis of 824 articles, as illustrated in Table 1, revealed that 57.6% of articles could be handled with computer vision while 12.8 percent were expected to be dealing with other information and communication technologies (ICT). In addition, 29.6 percent of articles were not able to cope with the technologies. With this regard, this study focuses on those risks mentioned by KOSHA regulations which could be tackled through computer vision. The scope of the paper is limited to the detection of positive and negative correlation of a worker with mobile scaffolding explained in article 68(1). Two case scenarios are explained to elaborate the proposed research concept.

4. CASE SCENARIOS

To identify the benefits of the proposed system, a construction entity (mobile scaffolding) which is almost used in every building construction site, was preferred for the experiment. The aim was to apply a computer vision-based risk recognition system developed for the detection of correlation between the construction entities.

The Article 68 (1): (Movable scaffolding) extracted from KOSHA said that “when the movable scaffolding is assembled by the employer, to prevent unexpected sudden movement or turning of the wheels of the movable scaffold, fix the wheel with a brake, wedge, etc., and fix the part of the scaffold to a solid facility or install an outrigger”. This article in KOSHA demonstrates the two correlation (positive and negative) between the mobile scaffolding and worker. The extracted case scenarios from this article can be mathematically written as follows

Case 1: For instance, if a person “A” is working on the mobile scaffolding “B” with outriggers installed, then the relation between the two entities is concluded as positive relationships and is safe for work.

Case 2: On the contrary, if the person “A” is working on the mobile scaffolding with no outriggers installed then the relationship between A and C is supposed to be negative. Consequently, the negative relation shows the unsafe arrangement and the system need to generate a warning message to the concerned safety manager automatically. Thus, the safety manager responsible for the mobile scaffolding safety will no more physically visit the job site.

5. DATASET ESTABLISHMENT

In order to train a CNN classifier, a huge number of labeled images are needed. Though, obtaining labeled images of construction objects from open-source databases is yet challenging. Thus, raw images of persons, mobile scaffolding (without outrigger and with outriggers) with an extensive range of variations such as lighting, shadow, etc. were collected. The raw images were taken from the Google database and one of the Tornado group's construction sites for higher secondary college of technology located in Abu-Dhabi, United Arab Emirates.

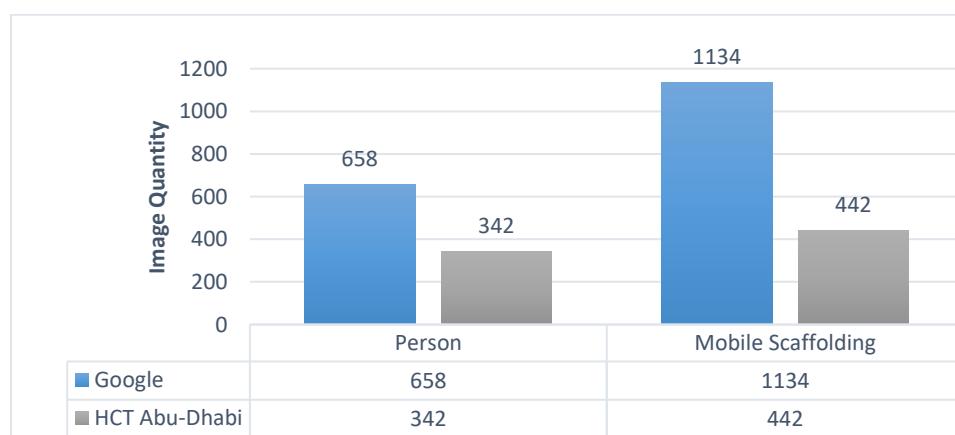


Figure 1. Distribution of image data source

A total of 3865 images were collected. Figure 1. depicts the detail statistics of each construction objects collected from two sources. To avoid overfitting, similar images from the identical scene were eliminated from the dataset during the annotation process. To detect the correlation among the resources in selected scenarios as a case example, three classes were defined: "scaffold" for mobile scaffolding, "safesc scaffold" for mobile scaffolding with having outriggers and "person" for a person. All the images (jpg, jpeg, png) in the database were labeled and saved as .json file format using standalone manual annotation software runs in a web browser called VGG Image Annotator (VIA) (see Figure 2.).

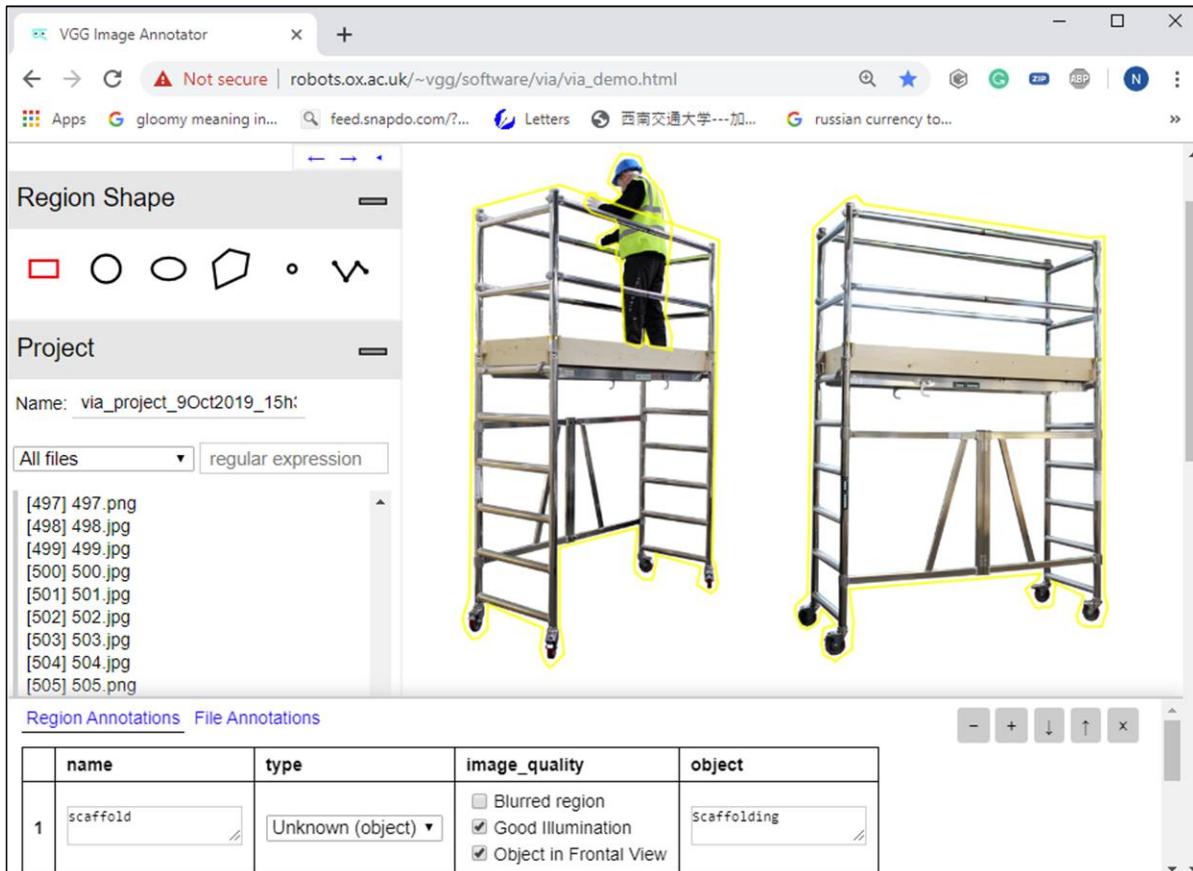


Figure 2. VGG Image Annotator (VIA): annotation tool

6. CONVOLUTION NEURAL NETWORKS APPLICATION

In recent years, many researchers have tried to focus on developing automated techniques for resource detection and tracking in a complex environment of construction [8], [9], [14]. The goal of these studies is to support operational effectiveness, increase productivity, safety enhancement and minimize idle time.

Convolution Neural Networks (CNN) have been used widely in object detection and classification due to the significance gained in the extraction of an image feature since rapid development witnessed in deep learning and other technologies. In the detection field, the accuracy and speed of object detection and classification are very important. Hence, many algorithms such as Region-CNN (RCNN), Fast RCNN, Faster RCNN came into existence, however, these algorithms require two-step processing [16] results in slow algorithmic speed, consequently, makes detection difficult in real-time. However, Faster RCNN has been found the best detection approach due to its ability of high accuracy. A major challenge confronting the CNN is its large dataset requirements for training. Likewise, the Mask R-CNN has been identified to outperform all the developed object detection approaches claimed by He et al. in 2017 [17].

Thus, to attain higher accuracy in terms of detection in a complex construction environment, the Mask-RCNN approach is applied in this research. Figure three shows the process flow chart of the proposed system. The annotated data is trained using the Mask R-CNN algorithm with 80 epochs and 300 steps per epoch. The results are quite impressive and can be seen in

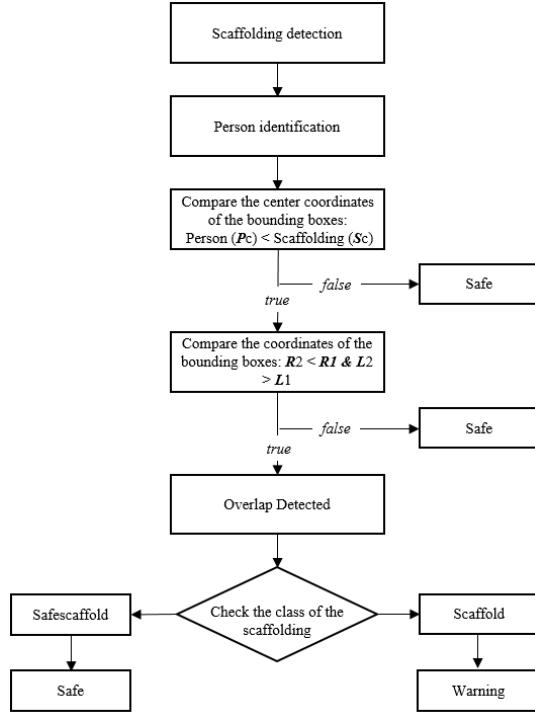


Figure 3. Process flow chart for correlation detection

7. Correlation Detection

This research introduces the overlapping method for correlation detection between the construction entity. Initially, the system detects and mask all the persons and scaffolding in a given image. After detection and segmentation, the center coordinates of both the bounding boxes are compared as shown in the figure....., if the person center coordinates "Pc" is greater than the mobile scaffolding "Sc", this means that the person is working on the ground and is safe to work. With the condition that person center "Pc" is lesser than the mobile scaffolding "Sc" then this implies the doubt of the relationship between the mentioned construction entities and will compare the corner coordinates of the two bounding boxes such as "L2" is greater than "L1" and "R2" is lesser than "R1", if both conditions satisfied then the system will detect the correlation else the action will be ignored. In order to identify the positive and negative correlation, the system will need to check the class of the scaffolding and decide accordingly.

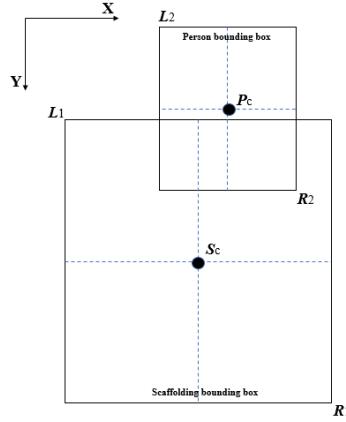


Figure 4. Example of bounding boxes coordinates

8. RESULTS AND DISCUSSION

The experiment was conducted on i7-9700k CPU, Ubuntu 16.04 LTS operating system, 32 GB memory, and Ge-Force RTX 2080 TI graphics card. A total of 3865 images were collected and manually annotated for model training. The qualitative results of the detection are illustrated in the below figures. It is clearly described from Fig.5 and Fig.6 that the trained model could localize the construction objects accurately.

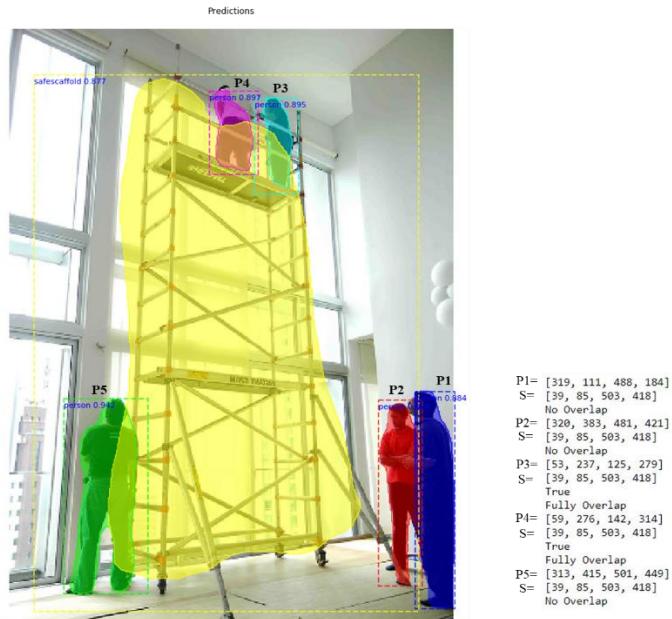


Figure 5. Case 1: Persons and Mobile scaffolding with outriggers having a positive correlation

Fig.5 exemplifies case 1 which includes the detection of persons and scaffolding with outriggers. The system initially detects the scaffolding and persons followed by determining the relationship using the overlapping methods discussed in section 7. Apart from construction entity detection, Figure 5. also illustrates the results of the correlation such as fully overlap for two persons P3 and P4. The detection results of case 2 are demonstrated in Fig. 6, which shows the negative correlation between the person and mobile scaffolding with having no outriggers.

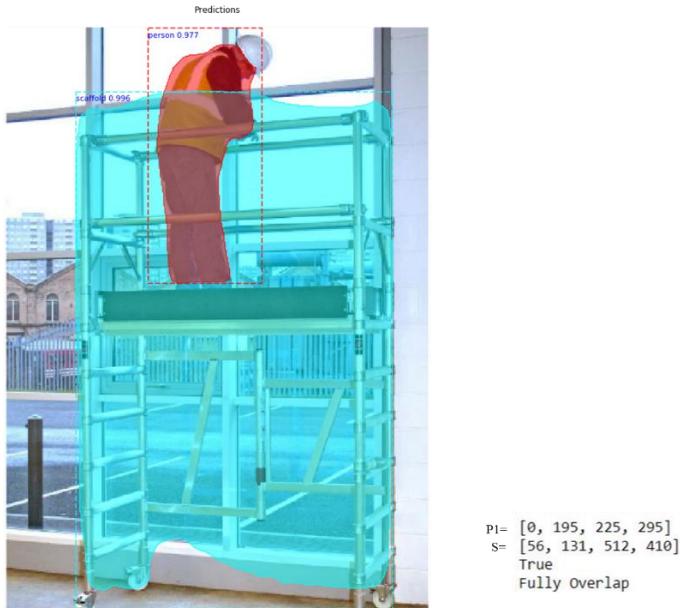


Figure 6 Case 1: Persons and Mobile scaffolding with no outriggers having negative correlation

9. CONCLUSION AND FUTURE WORK

Safety in construction is directly proportional to the lives of the worker. Generally, construction safety consists of two phases: safety planning and safety monitoring. The latter is of utmost importance due to its nature as a final layer of safety management. To improve that final layer of safety management, this paper proposed a novel system based on the extracted KOSHA rules leveraging deep learning algorithms to enhance risk recognition and accident prevention. To achieve this goal, KOSHA regulations are investigated and the relevant safety rules having relationship information are used as a base for image data collection. Images were collected from two different sources for the creation of dataset and model training. The developed correlation dependent risk recognition system has been successfully implemented on the two real scenarios taken from the accident reports. The preliminary results of the detection using Mask R-CNN algorithms are presented. In the future, a larger dataset from the real construction site will be created for the better detection of construction objects. In order to get a real reflection of the construction job site and more practical results in the end, the same framework will be extended to the accident cases from the database. It is further expected that the developed system could assess the safety performance if integrated with other technologies such as blockchain and IoT automatically.

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Ontology-based Safety Risk Interactions Analysis for Supporting Pre-task Planning

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Abstract: The construction industry remains serious accidents, injuries, and fatalities due to its unique, dynamic, and temporary nature. On workplace sites, Safety pre-task planning is one of the efforts to minimize injuries and help construction personnel to identify potential hazards. However, the working conditions are complicated. Many activities, including tasks or job steps, are executing at the same time and place. It may lead to an increase in the risks from simultaneous tasks. This paper contributes to addressing this issue by introducing a safety risk interaction analyzing framework. To accomplish this objective, accident reports of the Occupational Safety and Health Administration (OSHA) are investigated. The pairs of task incompatibility, which have time-space conflicts and lead to incidents, are found. Ontology technology is applied to build the risk database, in which the information is acquired, structuralized. The proposed system is expected to improve pre-task planning efficiency and relieve the burdens encountered by safety managers. A user scenario is also discussed to demonstrate how the ontology supports pre-task planning in practice.

Keywords: risk assessment, ontology, pre-task planning, simultaneous tasks

1. INTRODUCTION

Safety is critical for the construction industry. Jobsites are considered as one of the most dangerous places for workers. According to the Occupational Safety and Health Administration (OSHA), 971 of 4674 worker fatalities occurred in the construction industry (20.7%); that is, one in five worker deaths in 2016 occurred at construction sites[1]. The high injury rates and fatalities can plague productivity losses, cost overrun, and schedule. To solve these problems, The Construction Industry Institute funded a study and identified the essential components of an active construction safety program, including Demonstrated management commitment, Staffing for safety, Pre-projects and pre-tasks planning, Safety education and training, Employee involvement, Safety recognition and rewards, Accident/incident investigations, Substance abuse programs, and Subcontractor management [2].

Construction projects are characterized by complexity and a dynamic environment where many activities occur simultaneously. When two activities overlap in time and their workspace, incidents may occur by the risks is higher than considering each activity. For instance, They require adaptive safety measures to be ready in unexpected situations [3]. Practically, safety pre-task planning is demonstrated

as an effective method in preventing accidents and injuries by (1) define task sequence, (2) identifying, and (3) controlling potential hazards. Safety pre-task planning is usually applied to analyze every task daily, at the start of each work shift or work condition changes. Specifically, this includes defining a task sequence, identifying hazards and their respective control measures. An assessment of the plan's effectiveness is carried out after the completion of the work package.

Researchers put much effort into improving safety pre-task planning. Assessing potential risks have been studied, which proposed many aspects of levering hazards. For example, Jannadi and Almishari [4] developed a risk assessor model (RAM) to determine risks for significant construction activities, quantifying risks for 19 different construction occupations. Besides, innovative technologies are also applied to analyze hazards. The hazard analysis form is typically read and explained to workers in a pre-task work meeting. It takes time to deliver all contents in safety pre-task planning with vast and complex safety information. Consequently, the worker may start jobs while lacking information.

In order to address these limitations, ontology has offered to structuralize for presenting and reusing knowledge. Project employees can make decisions rapidly. The objective of this study is to consider the interaction among incompatible tasks. This paper proposed a framework for reassessing risks in safety pre-task planning.

2. LITERATURE REVIEW

2.1. Current construction safety pre-task planning

Many construction accidents and injuries occur due not to train in the proper process. A safety pre-task plan of all activities should be provided to measure risk in place. However, current safety pre-task planning requires safety employees to do many manual tasks. For example, the employees must know safety knowledge such as regulation, work sequence, historical accident and injuries data, and checklists. Hence, safety pre-task planning is complicated, time-consuming, and has to update when the schedule adjusts. It is hard to balance work results and safety concerns. On the other side, the information is unstructured, less updated, and complicated. It is challenging to deliver these safety contents with accuracy and efficiency.

2.2. Ontology-based knowledge in construction safety

Ontology can represent information in specific domains in comparison with the database schema and connect to other data sources semantically [5]. Knowledge reasoning and query are efficiently used in the ontology domain based on class, properties, and relationships. It can communicate with semantic web technologies and provide three significant advantages in information modeling [6]: (1) enhance versatility and extensibility of the model; (2) provide robust semantic representation and promote semantic interaction; and (3) promote grammatical inference and retrieval by enhancing concept-level retrieval requests.

The development of ontology in the construction industry aims to improve knowledge management. With explicit definition (concepts, attributes, relations), this technology can facilitate knowledge capture, storage, and query. In construction safety, ontology models usually apply in integrating with BIM. Wang et al.[7] expresses two reasons to adopt the ontology model to hazard analysis concept. (1) The hazard analysis concept has taxonomy similar to the form of class and properties in the ontology. (2) The relationship or non-relationship of each pre-task planning form can be reused.

2.3. Spatial and temporal interactions

In construction, activities have to follow sequences. It guarantees productivity, quality, and safety during the project. To maximize profits, contractors concern about how to improve productivity by optimizing time and space. It means that more activities can be producing. However, crowded job sites, resource constraints, and overlap activities may lead to higher safety risks. To decrease risks, Huang [8] adds safety design considerations into a multiple-stage site layout plan. The model was suggested to consider the influence of crane operations, hazardous materials, and travel routes on safety [9]. Although

these proposals could support to minimize risks, very few research contemplates the interactions among tasks [3].

Traditionally, despite the fact that temporal safety management has needed to involve schedule control, these are managed separately [10]. Recently, numerous other studies have put effort to link safety information and work schedule. Chau et al. [11] revealed that linking model between geometrical models with CPM or Bar-Chart, which supports predicting potential hazards. Especially, BIM 4D is a new emergence technology to implement in construction successfully. The integration of the 3D model and schedule brings to improve safety performance. Sulankivi et al. [12] linked falling accidents with a safety guard and railing installation schedule. Sloot et al. [13] demonstrated that 4D BIM could support the process of risk mitigation. However, few studies determine the hazards of simultaneous activities.

3. A FRAMEWORK FOR MUTUAL TASKS RISK REASSESSMENT

The primary purpose of this study is to propose a methodology that can support safety employees defines the potential hazards of mutual task conducting at the same time and place. The overall process is illustrated in Fig. 1. The first step is to collect safety incident cases. The database is usually stored through national data of each country. The pair of tasks incompatibility is extracted manually from the accident context description. Next, with the accident report and risk knowledge category, risk ontology is proposed and generated using the Protégé v5.5.0 tool. The main types include Task, Space, resource, risks. Accident cases are stored as an individual in the ontology. Lastly, it is converted to the RDF file for using the SPARQL tool. The query can show the pair of task incompatibility automatically and support safety employees to determine potential hazards.

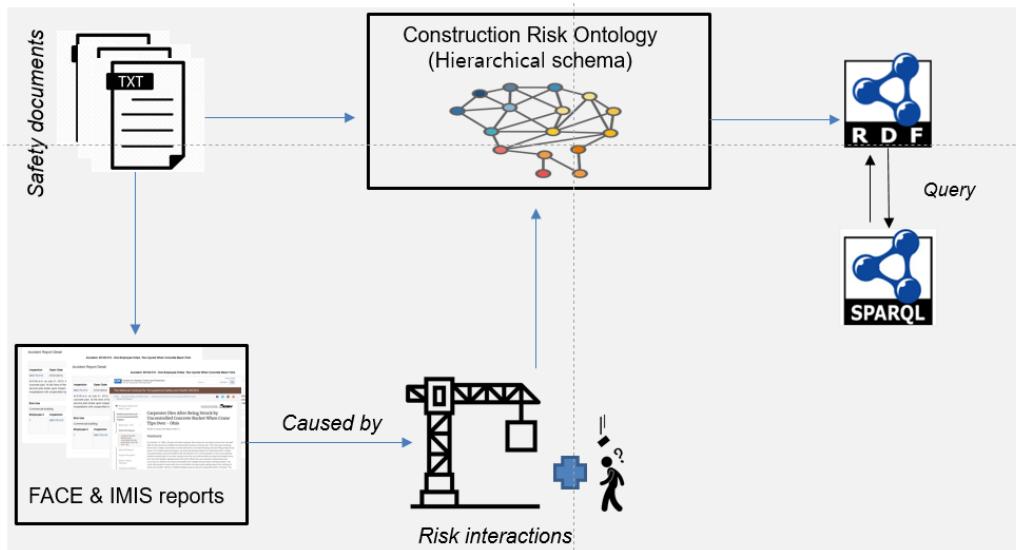


Figure 1. A framework for analyzing task compatibility or incompatibility

3.1. Information processing

To understand the scope and preparation for research, the author chooses two kinds of the database from Fatality Assessment and Control Evaluation (FACE) Program and The Integrated Management Information System (IMIS) from Occupational Safety and Health Administration (OSHA). Both FACE and IMIS databases have been categorized for the construction accident domain. Through the search engine of OSHA and NIOSH, each incident is determined by inspection or report number, and the group of accident cases can be found by keyword search. Fig. 2 shows the result of searching accident cases with detailed information, including description, type of accident, and inspection number.

Accident: 110937.015 - Employee Is Struck By Crane Outrigger That Fell Off Trailer

Accident: 110937.015 -- Report ID: 0626700 -- Event Date: 11/12/2018										
Inspection	Open Date	SIC	Establishment Name							
1359918.015	11/13/2018		Red Hook Conro Terminals Llc							
At 3:45 p.m. on November 12, 2018, Employee #1 was loading a flatbed trailer with crane outriggers. As Employee #1 was attempting to strap down the outrigger, the outrigger rolled off the trailer striking Employee #1. The load was not secured. The employee was struck by the crane outrigger and was killed from head injuries.										
Keywords: struck by, unstable load, crane outrigger, falling object, head, crane, unsecured										
Employee #	Inspection	Age	Sex	Degree	Nature	Occupation				
1	1359918.015	69	M	Fatality	Other	Laborers, except construction				

Figure 2. OSHA example for searching incident database

3.2. Safety Risk ontology

The safety risk ontology has been built using the Protégé v5.5.0 tool. Context information plays a vital role in construction safety. Based on previous research of Lee et al. [14], the underlying structure of the ontology consists of Task, Space, Resource, and Risk. Following four main classes, there are several sub-classes; for instance, *humane_resource* is a part of *Resource*, *Risk* class has a *degree*, *risk_factor*, *risk_prevention*. Fig. 3 describes the proposal schema of safety risk ontology.

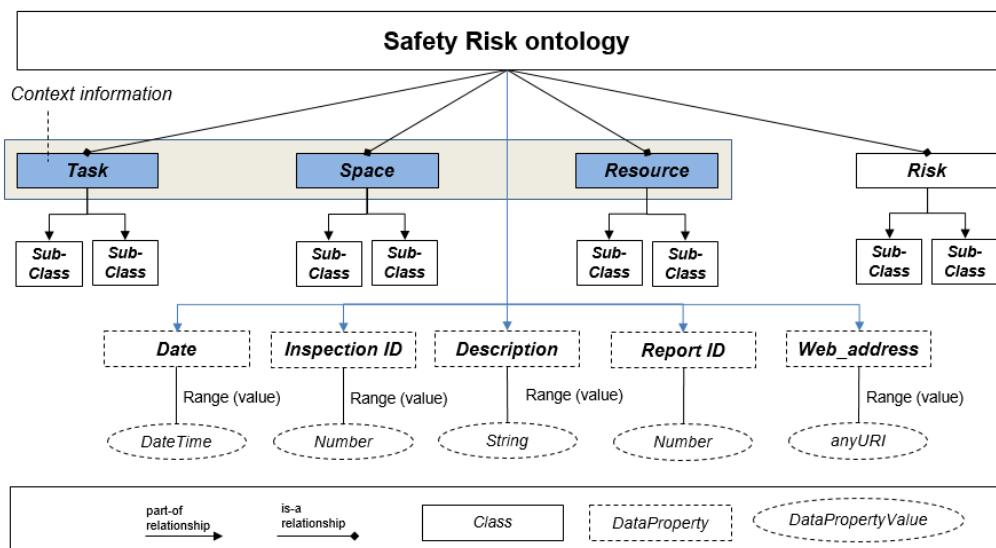


Figure 3. Safety risk ontology for assessing task incompatibility

4. IMPLEMENTATION

To demonstrate the feasibility of the framework, the author conducts to analyze accident reports with inspection number 1324218.015 from the IMIS database [15]. The collection template, as Fig. 4, is generated to categorize information for supporting ontology imported.

Report Title: Employee Is Killed When Struck In The Head By Steel Beam	
1 General information	
- Description	At 11:30 a.m. on June 20, 2018, Employee #1 was observing the crane's movement and placement of a steel beam. The steel beam disengaged from the crane's haul line and fell, striking the employee on the head. Employee #1 sustained a fractured skull and was killed.
- Event Date	06/20/2018

- Inspection ID	<i>1324218.015</i>
- Report ID	<i>0213900</i>
- Source	<i>https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=106661.015</i>
- Keywords	<i>Struck by, crane, head, falling object, steel beam</i>
2 Analyzing	
- The pair of tasks incompatibility	
+ Task A	<i>Deliver material</i>
+ Task B	<i>Inspection of the crane's movement</i>
+ Task C	
- Resource	
+ Equipment	<i>Crane</i>
+ Human resource	<i>Supervisor</i>
+ Material	<i>Steel</i>
- Risk	
+ Degree	<i>Fatality</i>
+ Prevention method	
+ Cause	<i>Struck by falling object/projectile</i>
- Space	
+ Exposure	<input checked="" type="checkbox"/>
+ Inside	<input type="checkbox"/>

Figure 4. Accident report collection template

By analyzing the accident report, adequate information is collected. *Delivery material* and *inspection of the crane's movement* are two tasks that occurred in the same time-space. Besides, context information also is filled in the template. Fig. 5 illustrated the accident case imported in protégé.

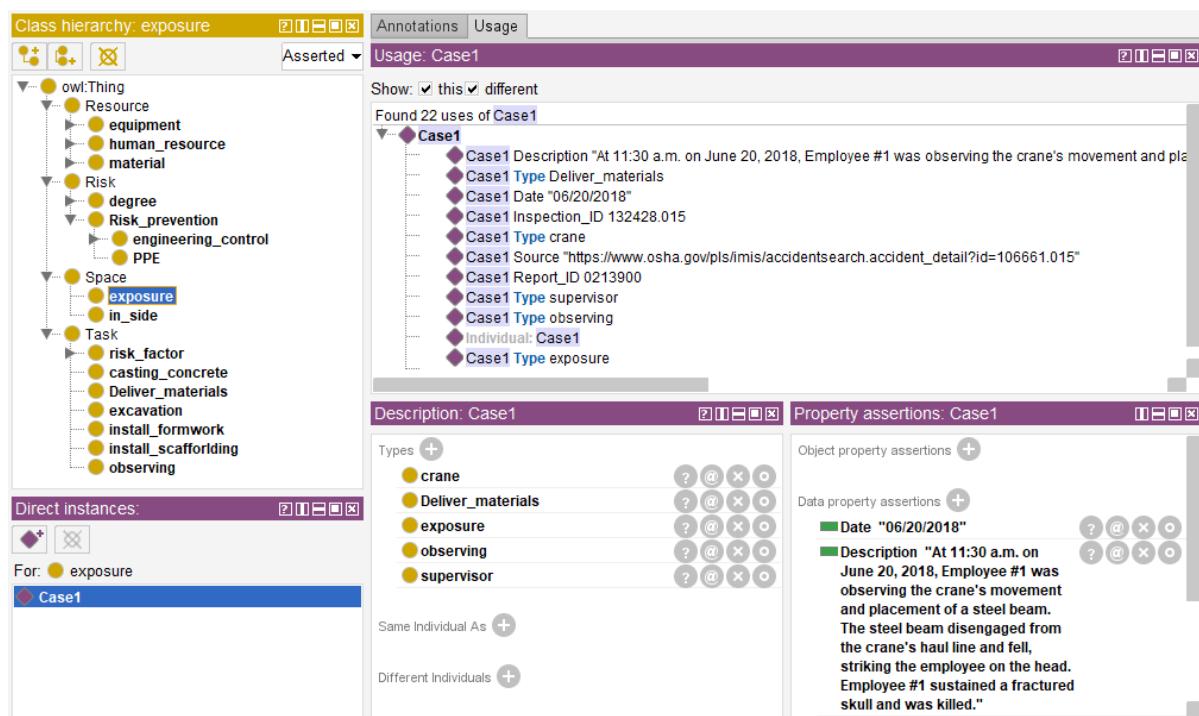


Figure 5. The screenshot of the example in protégé

5. DISCUSSION AND CONCLUSION

Simultaneous tasks are characteristic of construction work that aims to guarantee the project's cost, time, and quality. However, they lead to construction sites as the most complicated and dangerous workplaces resulting in fatal accidents and facing unexpected challenges to satisfy industry requirements. Hazard identification before work can play an essential role in decreasing accident rates. This study commenced by collecting accident reports from the OSHA database. Based on the analyses, the pair of task compatibility can support project employees' understanding and prepare prevention methods when conducting simultaneous tasks.

This paper conducts a preliminary analysis of a scenario that the task is delivering the material. Even though the preliminary studies revealed an accident occurred in the case of simultaneous tasks and a novel approach for building Safety risk ontology was proposed, it is still necessary to comprehensively analyze the full range of construction safety risks. As such, future developments will consider this. Furthermore, spatial and temporal interactions in the pair of task compatibility can be analyzed through innovative technology. Studies have been conducted on this ontology into BIM 4D. One of the ideas is to help the scheduler prevent risk when adjusting the schedule.

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Risk Identification and Management Strategies for BIM Projects

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Abstract:

The construction industry is undergoing a digital transformation in which Building Information Modelling (BIM) is a key technology. The potential of BIM in several areas such as design optimization, time management, cost management, and asset management/facility management (AM/FM) is widely acknowledged by the AECO (Architecture, Engineering, Construction, and Operation) industry around the world. However, BIM implementation in construction projects is faced with problems such as project delay and cost overruns. The lack of identification of risks in BIM projects and standard guidelines on mitigation techniques furthers poor performance, dissatisfaction, and disputes between employers and project participants, which results in low BIM adoption rates.

Therefore, the objective of this paper is to identify the potential risks in BIM implementation under the primary categories – (1) technical, (2) contractual, (3) management-related, and (4) personnel-related risks in BIM projects and present solutions to reduce, manage, and mitigate risks. To meet the objective of this paper, a survey was designed and conducted in the Hong Kong construction industry in which over 140 respondents from different disciplines, with experience in BIM projects, have participated. Based on the analysis of the survey data, the most severe and frequently occurring BIM risks and their potential mitigation strategies were identified and discussed in this paper.

Keywords: BIM Implementation, BIM Project Execution Plan, BIM standards, Risk Management

1. Introduction

The architecture, engineering, and construction (AEC) industry, often described as fragmented, complex, and risk-oriented is undergoing a digital transformation [1]. Building Information Modelling (BIM) is one of the primary technologies driving this transformation and is regarded as the future of the AEC industry [2]. The benefits of BIM in improving the quality of AEC projects and reducing project costs and delivery periods are well recognized in the AEC industry and the BIM research community [3]. However, several issues are commonly faced during BIM implementation at a project level due to the lack of standard guidelines (at the implementation level) on BIM implementation.

The AEC industry due to its inherent characteristics is a highly risk-prone industry [5]. Extensive studies on construction project risks can be found in the existing literature. Siraj and Fayek [6] have identified the main groups of risks in AEC projects as- (1) management-related, (2) technical, (3) delivery method related, (4) resource-related, (5) site condition related, (6) contractual or legal, (7) financial, (8) social, (9) political, (10) environmental, and (11) health & safety-related. Siraj and Fayek [6] further identified the top ten risks in each category such as ‘poor coordination among various parties involved in the project’ and ‘design errors and poor engineering’ as the highest-ranked risks in the management-related and technical categories respectively. The relation of risks to the size, structural, and technical complexities of projects is well-identified in existing literature [7]. Banaitiene and Banaitis identified that controllable risk sources could be further broken down into seven sub-categories as- (1) design, (2) external, (3) environmental, (4) organizational, (5) project management, (6) right of way risks, and (7) construction which fall within the control of the project team [8]. Zou, Zhang and Wang identified that many project risks were repeated among five categories as- (1) cost-related, (2) time-related, (3) quality-related, (4) environment-related, and (5) safety-related [9]. BIM technology due to its technical complexities and widespread effect on/relation to several processes and roles in AEC projects, adds significantly to project risks, and may severely project hinder performance if not implemented effectively [10]. For example, the need for a well-defined legal framework [4] and guidelines to facilitate the transition from existing technologies (CAD) to BIM [11] to sustain/improve project quality is strongly advocated by researchers. Therefore, this research is motivated to investigate the factors of risks associated with BIM implementation to aid project stakeholders to strategize and make informed decisions to optimize BIM implementation.

The research conducts an industry-wide survey of the Hong Kong AEC industry to identify BIM implementation risks, analyze the severity and likelihood of occurrence of risks in BIM projects, and present corresponding mitigation techniques. 140 respondents with extensive experience in BIM projects have participated in this survey. Four categories of BIM implementation risks namely (1) technical (such as inefficient data interoperability), (2) contractual (such as model ownership), (3) management-related (such as inadequate top management commitment), and (4) personnel-related (such as lack of skilled personnel), identified from existing literature [10] are included in the survey.

Based on the survey results, a total of 26 BIM implementation risks are identified, ranked, and supported with mitigation techniques. A risk-analysis matrix mapping the likelihood of BIM implementation risks to their severity (effect on projects) is developed.

2. Research Methodology

The methodology of this research includes a systematic survey of the Hong Kong AEC industry. By conducting a systematic survey, this study identifies the most important risk factors of BIM adoption in construction projects and proposed mitigation approaches. The survey questionnaire has mainly three parts. The first part collects personal particulars of the survey respondents such as business nature, position, duties in their organizations, year of practical experience in using BIM, and the number of BIM projects worked in. The second part provides the respondents with a list of 26 types of risk (identified from existing literature) categorized under 4 categories namely, (1) technical, (2) contractual, (3) management-related, and (4) personnel-related. The four categories of 26 types of risks are summarized in this study based on literature review and considerations of the aspects about legal, contractual & legislation, the responsibility of stakeholders, reliability of data, standardization of BIM, BIM model/data ownership, intellectual property rights, and technical issues through literature reviews. The survey respondents have the option to choose the most important risks from the list provided to them or may specify additional types of risk based on their experience. The third part of the survey provides the respondents with a list of 11 risk mitigation strategies in total, which are derived in this study based on practical experience. The respondents are allowed to specify additional methods of mitigation if they consider appropriate.

The targeted survey respondents are on an individual basis. The majority of survey respondents have practical experience of working in BIM projects and are from different backgrounds and disciplines. In the survey, respondents need to specify the business nature of their occupations. Table 1 shows the options of business natures in the survey questionnaire, the group of which is based on the common knowledge of the authors on the industry. Multiple selections of business nature are allowed if the respondents consider appropriate. The survey questionnaire was distributed in a Word document format for the respondents to return by either handwriting or computer typewriting. The channel of distribution of the survey questionnaire was mainly electronic mail and hardcopy. The targeted number of returns of the completed survey questionnaire with valid input in this research is a hundred.

Table 1. Grouping of Business Nature

No.	Group	Inclusion
1	Government or Statutory Body	Government or Statutory Body
2	Developer	Developer
3	QS Consultant	QS Consultant
4	AEC Consultant	Architect, Designer, Engineer
5	Contractor	Main Contractor, Sub-Contractor
6	Supplier	Material Supplier, Manufacturer
7	BIM Consultant	BIM Consultant, BIM Trainer
8	Software Vendor	Software Developer, Information Technology (IT) professional
9	Insurance Provider	Insurance Provider
10	Academia	Academia

3. Results and Discussions

The survey questionnaire responses were collected via emails from February 2019 to March 2019. Every survey questionnaire was given to the respondent only upon s/he had confirmed his/her willingness of support. A total of 165 persons were contacted and a total of 149 completed survey questionnaires were collected. The distribution of the years of experience in BIM projects of the respondents is shown in Table 2. From the result, most of the respondents (69.8%) have over 3 years of experience, while 21.5% of the respondents have over 10 years of experience.

Table 2. Years of Experience in BIM projects of Respondents

Years	Count of Respondent	Percentage
0 – 3	45	30.2
4 – 6	38	25.5%
7 – 10	34	22.8%
11 – 15	22	14.8%
>15	10	6.7%
Total	149	100%

Table 3. BIM Projects involved of Respondents

Nos. of BIM project	Count of Respondent	Percentage
0	6	4.0%
1 – 10	88	59.1%
11 – 20	27	18.1%
21 – 30	10	6.7%
31 – 50	7	4.7%
51 – 100	7	4.7%
101 – 200	3	2.0%
> 200	1	0.7%
Total	149	100%

The distribution of the numbers of BIM projects of the respondents is tabulated in Table 3. As shown in Table 3, most of the respondents had involvement in 1 to 10 projects (59.1%) or 11 to 20 projects (18.1%). 6 respondents had no past involvement in any BIM projects. Table 4 shows the numbers of the respondents per group. Multiple selections of business nature per respondent are allowed. Most of the respondents are in the groups of BIM Consultants (29.6%), Contractor (24.6%), and AEC Consultant (13.4%) respectively.

Table 4. Business Nature of Respondents

No.	Group	Count	Percentage
1	BIM Consultant	64	29.60%
2	Contractor	53	24.60%
3	AEC Consultant	29	13.40%
4	Software Vendor	25	11.60%
5	Developer	22	10.20%
6	Government or Statutory Body	10	4.60%
7	Academia	6	2.80%
8	QS Consultant	3	1.40%
9	Supplier	2	0.90%
10	Insurance Provider	2	0.90%
Total		216	100%

Table 5 shows the numbers of the respondents grouped by their position and duties in their BIM projects. Multiple selections per respondent are allowed. As shown in Table 5, the major position and duties groups of the respondents are Discipline BIM Team Leader & BIM Coordinator (18.6%), Project BIM Manager (14.0%), Project Director & Project Manager (13.1%), and BIM Trainer (11.0%).

Table 5. Position & Duties in BIM Projects of Respondents

No.	Position	Count	Percentage
1	Discipline BIM Team Leader, BIM Coordinator	44	18.60%
2	Project BIM Manager	33	14.00%
3	Project Director, Project Manager	31	13.10%
4	BIM Trainer	26	11.00%
5	Software Vendor	18	7.60%
6	Employer (Owner)	16	6.80%
7	QS Consultant	14	5.90%
8	BIM Modeller	14	5.90%
9	Design (Architectural) Consultants	13	5.50%
10	Engineer (Contractor Engineer)	11	4.70%
11	Engineering Consultant	7	3.00%
12	BIM Auditor	7	3.00%
13	Insurance Provider	2	0.80%
Total		236	100%

4. Risk identification

From the total 26 types of risk, 9 types belong to technical (Identity No. from T1 to T9), 6 types belong to contractual (Identity No. from C1 to C6), 9 types belong to management-related (Identity No. from M1 to M9) and the remaining 2 types belong to personnel-related (Identity No. P1 and P2). Each respondent is allowed to select a total of five risks. The summation of the risk counts is therefore 149 respondents multiplied by 5 selected risks for each respondent, which equals to 745 in total. Table 6 shows the ranking of the total 26 risks based on their counts of being selected.

Table 6. Ranking of 26 risks based on Consequence

Rank	Count	likelihood	Risk with Identity No.	Category
1	69	3.84	C6. Poor participation / contribution from project team in BIM adoption	Contractual
2	57	3.44	C1. Unclear requirements (e.g. Employer's Information Requirements (EIR) / Asset Information Requirements (AIR) / contract) of BIM uses and specifications	Contractual
3	54	3.58	C2. Unclear roles, responsibility and liability in BIM implementation	Contractual
4	52	3.75	P1. Lack of adequate expertise in BIM	Personnel
5	45	3.64	T6. Design conflict / clashes in BIM was not revealed / unresolved	Technical
6	42	3.18	C5. Unclear legal liability	Contractual
7	41	3.15	T8. Wrong information from BIM model	Technical
8	39	3.15	C3. Unclear workflow of BIM process	Contractual
9	35	3.33	T5. Mistakes in design drawings/shop drawings generated from BIM	Technical
10	31	3.11	T4. Information loss or damage from BIM because of data exchange	Technical
11	30	3.21	T9. Lack of interoperability	Technical
12	26	3.13	M2. Incorrect cost estimation in tendering from BIM	Management
13	24	3.13	M3. Misunderstandings because of poor communication through BIM	Management
14	22	3.07	C4. Unclear definition of BIM Level of Development (LOD)	Contractual
14	22	3.23	M9. Information flooding	Management
15	20	2.79	T3. Cannot get information from BIM due to software versioning	Technical
16	17	3.40	P2. Turnover and stability of key person in BIM implementation	Personnel
17	15	3.07	M1. Poor task sequencing for inputting into BIM	Management
17	15	2.73	M6. Project delay because of preparing BIM models	Management
18	13	2.29	T2. Information loss from Common Data Environment / BIM Server	Technical
18	13	2.41	T7. Bugs in BIM software that lead to a financial loss	Technical
18	13	2.73	M4. Economic loss because of poor BIM management	Management
18	13	3.00	M7. Poor construction progress tracking	Management
19	11	2.56	T1. Information loss from BIM because of disputes	Technical
20	9	2.64	M5. Poor construction quality	Management
21	5	2.97	M8. Project cost over budget	Management
Total	745			

As shown in Table 6, the top five risks in terms of the number of times selected by respondents (counts) are – (1) (C6) poor participation/contribution from the project team in BIM adoption, (2) (C1) unclear of requirements of BIM uses and specifications, (3) (C2) unclear roles, responsibility, and liabilities in BIM implementation, (4) (P1) lack of adequate expertise in BIM, and (5) (T6) design conflict/clashes in BIM not revealed or unresolved. The top three risks belong to the contractual risk category, the fourth

risk is personnel-related, whereas the fifth risk is technical. The results indicate that the most concerning risks are contract-related which may be due to the lack of adequate contractual provisions such as clarity in obligations and responsibilities of the project participants in the contract or agreement. The current government policies include the Technical Circular (Works) issued in 2019 by the Development Bureau of the HKSAR Government for the adoption of BIM for capital works projects in Hong Kong. There are limited standards and contractual documents for BIM implementation, including those mainly issued by the Construction Industry Council, Government Works Departments and some major public and private developers in Hong Kong. The situation may be improved by clearly defining and integrating the employer information requirement and enhancing the contract or agreement for performing BIM services between the contracting parties. For example, clear obligations, liabilities, and responsibilities between project participants and the availability and enhancement of government policies and guidelines for proper implementation. The bottom-most or the least concerning risks related to BIM projects are found to be from the management-related category. As shown in Table 6, the survey has identified management-related risks such as project cost going over budget (M8) and poor construction quality (M5) as the least concerning risks related to BIM adoption. We can assume that for the success of BIM adoption, project cost over budget is not a major concern. In terms of likelihood of occurrence of the risk (chance of happening), the top five risks are the same as that in terms of count as shown in Table 6 and information loss from Common Data Environment / BIM Server (T2) was identified as the least concerning risk.

Based on the survey results, a Risk Analysis Matrix (as shown in Table 7) is constructed according to the systematic risk management process introduced in the Risk Management for Public Works - Risk Management User Manual [12]. The structure of this Risk Analysis Matrix is that the X-axis indicates the level of the consequence of the risks (counts of the risk being selected) and the Y-axis indicates the level of likelihood of the risks. The two axes indicate the correlations between the consequences and likelihood of the risks. With reference to Table 6, the classification for the consequence of risk is that risks have “above 50 counts” to be first range “Catastrophic”, “between 39 and 50 counts” to be second range “Major”, “between 24 and 38 counts” to be third range “Moderate”, “between 10 and 23 count” to be fourth range “Minor”, “under 10 counts” to be fifth range “Insignificant”. Meanwhile, for each of the total 26 risks was graded by the respondent by using a 5-point Likert scale to select either “5 Frequently Happen”, “4 Likely Happen”, “3 Possible Happen”, “2 Unlikely Happen”, “1 Rare Happen”. The classification for the risk likelihood is that “above 3.60” to be first range “Frequent”, “between 3.33 and 3.60” to be second range “Likely”, “between 3.00 and 3.32” to be third range “Possible”, “between 2.56 and 2.99” to be fourth range “Unlikely”, “below 2.56” to be fifth range “Rare”.

Table 7. Risk Analysis Matrix

		Consequences of the Risk				
		Insignificant	Minor	Moderate	Major	Catastrophic
Likelihood of the Risk	Rare		T2, T7			
	Unlikely	M5, M8	T3,M6,M4,T1			
	Possible		C4,M9,M1,M7	T4,T9,M2,M3	C5,T8,C3	
	Likely		P2	T5		C2, C1
	Frequent				T6	C6, P1

From the Risk Analysis Matrix, it is concluded that Extreme High Risks are C6 (Poor participation/contribution from the project team in BIM adoption) and P1 (Lack of adequate expertise in BIM). Very High risks are C2 (Unclear roles, responsibility, and liability in BIM implementation), C1 (Unclear of requirements of BIM uses and specifications), and T6 (Design conflict/clashes in BIM was not revealed / unresolved). The results echo the analysis and assumptions under Table 6, indicating that stakeholders are recommended to pay attention to contractual issues to achieve their objectives of BIM adoption efficiently. Moreover, in response to P1, we can expect that appropriate BIM training and educations of BIM personnel will be the solution and both software-based training & project-based training should be considered. For T6, the solution can be the enforcement in adopting BIM software to facilitate design coordination together with appropriate training for the use of the BIM software.

5. Conclusion

According to the top-ranked three risks from the overall perspective (take into account all groups of respondents), which are C5 (Poor participation/contribution from the project team in BIM adoption), C1 (Unclear of requirements of BIM uses and specifications), and C2 (Unclear roles, responsibility, and liability in BIM implementation), it can be clearly stated that the most important risks are mainly relating to contractual issues. Contractual documents of BIM requirements play a critical concern in the Hong Kong construction industry when adopting BIM technology. Prompt availability of government policy and associated contractual documents to the industry are recommended and project clients shall play a key role to enforce such contractual documents to fully realize the potential benefits and advantages of adopting BIM technology in the projects. The results also show that the industry lacks adequate expertise in BIM and some technical risks like design conflict were not revealed or unresolved. The AEC industry and its stakeholders can consider the recommendations suggested above.

It is the first step of the survey study on the topic of Risk Identification and Management Strategies for BIM Projects. For future work, more comprehensive insights could be discovered by an in-depth analysis of the collected data. For example, analyses can be conducted within groups of respondents as well as across groups, based on factors such as business nature and years of experience. Meanwhile, some arrangements may help to produce better results by further sub-grouping the data based on the nature of the business. For example, “Main Contractor” and “Sub-contractor” could be sub-grouped in analyses as they are at different positions of the supply chain and have different interests. In addition, dividing the group “Government / Statutory Body” into “Authorities / Regulators”, “Quasi-government” and “Works Departments” may help, because they play different roles in the ecosystem of a BIM project. On the other hand, for the position and duties of Respondents, offering more options for example “Project Coordinator” and “Technical Officer” were requested by some respondents in the survey and may be considered in the future.

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V. VISUALIZATION IN AEC INDUSTRY (B2)

The effectiveness of HMD-based virtual environments through 3D camera for hotel room tour

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Abstract: Many of hotel customers obtain information from hotel websites to find the best alternative. One of the crucial information for the choice is spatial/visual information of hotel rooms. However, hotel website provides photographs only showing representative room features that may not be sufficient to give a full understanding of hotel room to customers. HMD-based 3D virtual environments (HVE) created by 3D camera could improve customers' experiences of hotel rooms by providing full virtual tours of hotel rooms. However, to the best of our knowledge, whether HVE can adequately provide similar customers' perception on spatial/visual information remains unproven as physical hotel rooms. The present study thus aims to verify how similar and reliable information on physical hotel room HVE provides to hotel customers in comparison with hotel website with 2D photograph and display-based 3D virtual environment. For this purpose, this study conducted a comparative experiment to investigate perception of three environments. As a result, the study found that HVE is more effective to provide spatial/visual information as similar as an actual hotel room. In addition, HVE increases customers' perceptions towards the reliability of information, the quality of hotel room and intention to book.

Key words: Virtual Reality, Head-mounted Display, 3D camera, Virtual tour, User perception

1. INTRODUCTION

As the importance of Online Travel Agencies (OTAs) has been growing, most of hotels provide room photographs on their websites, which help customers check rooms before making a reservation. However, these photographs are usually not sufficient to give full information on hotel rooms to customers. Such lack of information could give rise to customer's perceived gap in room features such as space layout, furnishing between online photographs and the actual rooms. The perceived gap could lead to customers negative impression (e.g. disappointment and dissatisfaction) on the hotel.

The recent technology, 3D camera, in this regard has a potential to mitigate the perceived gap by creating realistic virtual environments. 3D camera captures visual (e.g., color and texture) and spatial (e.g. dimensions and locations) data of a physical space in an accurate and instant manner. The captured data are then uploaded to a cloud server for processing, computing and generating virtual environment, thereby providing consistent information between the virtual environment and physical environments [1,2]. This technology supports a walkthrough function through which customers can navigate and gather further information in the virtual environment [3,4]. The generated virtual environments are usually experienced through display on computer screen or Head-Mounted Display. With the advancement of immersive virtual reality technologies, HMD-based 3D virtual environments (HVE) draw more attention in recent years. Indeed, studies in diverse fields proved the usefulness of HVEs [5-7] and some of hotels are recently employing HVEs in their hotel website.

However, whether HVEs can adequately represent physical hotel environments for providing similar customers' perception on room features remains unproven. To address the gap, this study aims to evaluate how similar and reliable the obtained information from the experiences of the three environments (i.e., hotel website with 2D photographs (HWP), display-based 3D virtual environment (DVE) and HVE) are to actual hotel room. For this, we created a virtual hotel room using 3D camera and conducted an experiment to compare perception on spatial/visual information of three environments. Since this study is an on-going project and only small number of subjects participated in the experiment, a preliminary analysis result is presented in this study.

2. RESEARCH METHOD

2.1 Experiment setting and participants

A hotel room of Hotel ICON in Hong Kong was selected as a test-bed. The hotel room involves regular hotel room facilities such as a television, a toilet, chairs, a desk, a bed, closet and both natural and artificial light. A room description page of the hotel website was used for the experience of HWP. A Matterport 3D camera was used to capture the hotel room and then create a virtual environment for the experience of DVE and HVE. The created virtual environment was uploaded to the hotel website instead of 2D photographs for the experience of the DVE. Participants then used a mouse to move and look around and draw/draw back curtains in the virtual environment. Lastly, Samsung Gear VR was used for experience of the HVE. Figure 1 shows 3D scanning of the Hotel room and the experiment. For the experiment, ten participants were recruited by advertising through a poster at the Hong Kong Polytechnic University. The participants have been rewarded a gift coupon for their participation. The participants were undergraduate and graduate students at the Hong Kong Polytechnic University from the ages of 18-22 years old. Six of them are man and rest of them are women.



Figure 1. 3D scanning of the hotel room and the experiment.

2.2 Experiment Procedure

Before the start of the experiment, participants read and signed a consent form for agreeing participating in the experiment. Then, they were given a training tutorial on how to use Samsung Gear VR and how to navigate in the HVE. A within-subject study was designed for this experiment. Participants experienced three environments (i.e., HWP, DVE, and HVE) for two minutes respectively in a random order. After all the experience of the three environments, participants walked and looked around the actual hotel room to evaluate how similar and reliable the obtained information from the experiences of the three environments were to the actual hotel room. Each participant was asked to perform three comparative evaluations on room features as shown in Table 1: the actual hotel room (baseline) versus HWP, DVE, and HVE. In addition, questions regarding intention to book and the reliability of the obtained information from the experience of three environment were also asked.

Table 1. Hotel room features for comparative evaluation.

Hotel room features
Cleanliness of guest room (bedding, carpet, furniture, etc.)
Cleanliness of bathroom
Space layout of guest room

Window view of guest room
Size of guest room
Size of bathroom
Interior design of guest room (furniture, interior accessories, etc.)
Room facilities (Air conditioning, electronic appliances, safety box, etc.)
Bathroom amenities (presence of bathtub, shower booth, etc.)

3. RESULTS AND DISCUSSION

Because of the limited number of participants, this study only presents the mean values of each question of room aspects of the three environments. The analysis results are shown in Figure 2. As expected, the results show that the HVE provides more similar spatial/visual information to the actual hotel room compared to DVE and HWP. Although DVE shows higher similarity than HVE to the actual room in a few room features, they are confined to the room aspects of bathroom. In case of ‘Window view of guest room’, we think ease of viewing through window at various angles using mouse may affect the results.

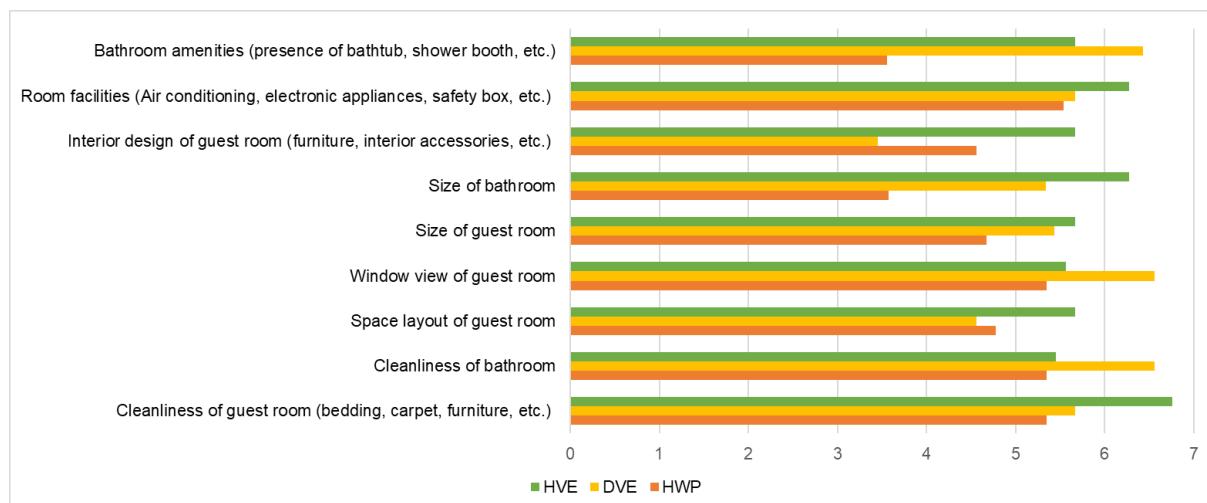


Figure 2. The results of perceived similarity on spatial/visual information between an actual hotel room and three environment

In addition to the perceived similarity, the results of the preliminary analysis indicate that participant felt HVE and DVE more trustworthy in terms of the obtained information from the experience as shown in Figure 3. Similarly, participants feel more positive on intention to book and the quality of the hotel room in HVE and DVE. Although these findings were not derived from the statistical analysis, mean differences of variables of rooms features are distinctive.

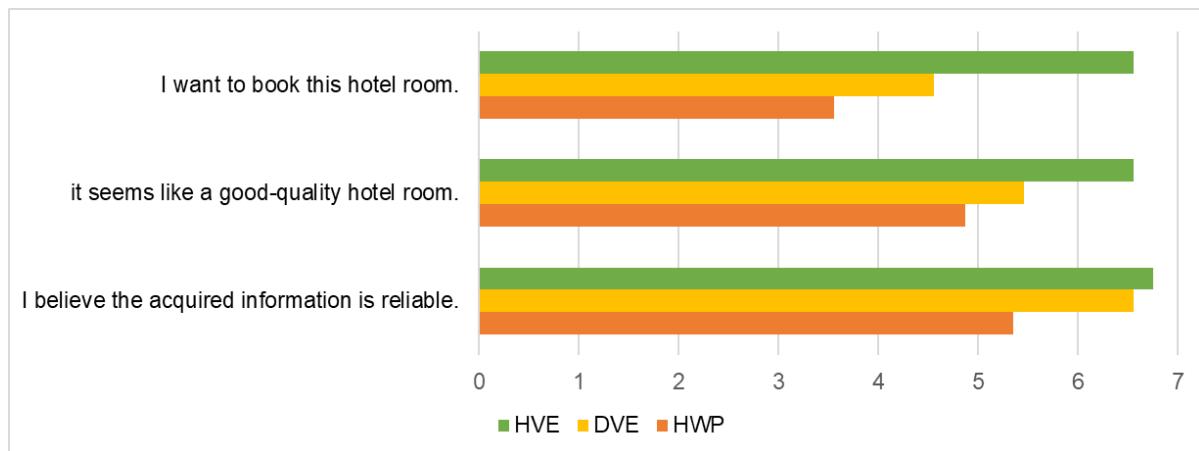


Figure 3. The results of intention to book and reliability of the information

4. CONCLUSIONS

This study conducted an experiment to compare perception of three environments (HWP, DVE, HVE) and then to verify the feasibilities of whether HVE can be used for inspecting hotel rooms online. The main outcomes of this study are that HVE is more effective to provide spatial/visual information as similar as an actual hotel room. In addition, HVE increases customers' perceptions towards the reliability of information, the quality of hotel room and intention to book. These results provide the potential of online room inspections using HVE to hotel business. Furthermore, this new practice of using 3D virtual technologies can thus develop new communications between hotels and customers within the hotel industries. The survey in this study is, however, based on a small number of participants. In addition, the results were obtained from subjective questions. To address this issue, further studies are required using various psycho-physiological sensors that objectively examine participants' emotion and engagement with larger number of experiment sample.

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A VR-Trainer for Forklift Operation Safety Skills

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Abstract: This research investigates how a Virtual Reality (VR)-based simulation could be used to train safe operation skills for forklift operators. Forklift operation is categorized as high-risk work by many occupational health and safety regulators and authorities due to high injury and fatality rates involved with forklifts. Therefore, many safety guidelines have been developed for forklift operators. Typically, forklift operation safety training is delivered based on instructional texts or videos, which have limitations in influencing people's safety behavior. Against this background, we propose a VR-based forklift simulator that can enable safe operation skills training through a feedback system. The training program consists of several modules to teach how to perform the basic tasks of forklift operation, such as driving, loading and unloading, following the safety guidelines. The system provides instantaneous instructions and feedback regarding safe operation. This training system is based on the model of "learning-by-doing". The user can repeat the training modules as many times as necessary before being able to perform the given task without violating any safety guidelines. The last training module tests the user's acquisition of all safety skills required. The user feedback from several demonstration sessions showed the potential usefulness of the proposed training system.

Key words: Virtual Reality (VR), training, forklift, safety

1. INTRODUCTION

Forklifts are used in various workplaces to transfer, lift and stack different types of loads. Despite their versatility and usefulness, forklifts are often involved with incidents, and the resulting human and financial cost of forklift-related incidents is substantial¹. According to a research paper analyzing 14,625 occupational fatalities involving machinery from 1992 to 2010 in the US, 1,487 fatalities (10% of all fatalities investigated) were involved with forklifts for the period of time, making forklifts as the type of machine involved with the second largest number of deaths after tractors [7]. Due to such high injury and fatality rates involved with forklifts, forklift operation is categorized as high-risk work by many occupational health and safety regulators and authorities around the world.

Forklift operation requires the operator to have a high-level of safety skills. To increase forklift operators' safety skills and awareness, many safety guidelines and best practices have been developed and used for training purposes. Typically, these guidelines are communicated through verbal/visual instructions or in texts such as Code of Practice². In this background, the use of Virtual Reality (VR) for forklift operation training has recently been proposed, and several prototypes have been developed

¹ <https://www.safework.sa.gov.au/sites/default/files/forkliftsafety.pdf?v=1527223033>

² <https://www.safeworkaustralia.gov.au/system/files/documents/1703/industrial-lift-trucks-general-guide.pdf>

[2][12][13]. However, these prior works were mostly focused on the visualization of potential dangers and safety risks, and they were limited in providing a learning environment in which the user can acquire transferrable, “hands-on” safe operation skills.

To address the issue, we propose a VR-based forklift simulator that can enable safe operation skills training through a feedback system. The system has its conceptual basis on the idea of “learning-by-doing”. The training program consists of several modules, through which a user can learn how to safely perform the basic tasks in forklift operation, including basic driving, loading and unloading, while getting instantaneous instructions regarding safe operation and feedback on how they are performing. The rest of this paper provides the details of the concept and design of the prototype developed.

2. RELATED WORK

2.1. VR-based Training

Over the last two decades, VR systems have been increasingly accepted as a promising training platform for many industrial skills. The use of VR for training has been found to have a range of benefits when compared to traditional training approaches. A VR-based training environment can provide the user with a unique learning experience combined with multi-sensory inputs such as vision, sound, and haptics [4]. Also, a VR-based training system can enable “learning-by-doing” when such a form of learning is difficult to implement in the real environment due to the availability of equipment or facility, safety concerns, or cost constraints [4]. Due to these perceived benefits of VR-based training, several prototypes have been developed and tested for various applications, including surgical skill training [8], industrial assembly and maintenance skill training [3][4], and manufacturing system operation training [11], to name just a few. Most of these earlier works have demonstrated that a VR-based training system would be an effective alternative to traditional training methods such as instructional videos.

Gavish et al. [4] found that people trained in the VR platform outperformed the people trained based on an instructional video in terms of the error rate. Brough et al. [1] found similar results in the context of mechanical assembly operations. An extensive review found that there is clear evidence that the surgical skills (e.g., endoscopy and laparoscopy) acquired through a VR simulator-based training are transferred to actual operation room environments [8]. Additionally, Stefanidis et al. [9] found that trainees who received a proficiency-based laparoscopic training in a VR simulator retained the skills for the long term.

2.2. VR-based Training for Safety Skills

Many researchers suggested that VR-based training can be particularly useful for safety skills training for high-risk industrial activities, such as construction or mining [14], incident response [10], and industrial facility maintenance and operation [3][6]. This is because a VR-based approach can be an effective way to create a hazardous situation without posing a real safety risk to the trainee and train a person regarding how to behave and respond to the hazards in the situation through simulation. Most of the earlier developments of VR-based training system focused on the visualization of the hazardous situation and training skills related to what to do in response to the hazards. Specifically, skills related to risk identification, risk evaluation, and risk response planning were focused in the earlier works [5]. VR-based safety training has been found to have benefits in improving worker safety performance and also in terms of training cost [3]. However, it has been suggested that more future works are required to develop a VR-based safety training program that can cover all the risk management phases (i.e., risk recognition, risk evaluation, risk response planning, and risk controlling and monitoring) [5]. Several researchers have particularly emphasized the importance of realistic scenarios [5] and the facilitation of interactive learning [10][14] in VR-based safety skills training.

Several VR-based forklift simulators have also been developed for operator safety skills training purposes. The prototype developed by Yuen et al. [12], for example, included a few case scenarios of ‘virtual accidents’, but it was not designed to provide any instantaneous feedback to the user regarding their detailed actions. Similarly, the prototype developed by de Villiers and Blignaut [2] included a few scenarios simulating dangerous situations. In their simulator, the user can see his/her safety performance after the simulation is finished. A review of previous examples of VR-based forklift operation simulators revealed that prior works mostly focused on the visualization of hazards and training how to respond to the hazards in the given situation, but they have weakness in the aspect of interactive learning within the VR environment.

3. DESIGN OF VR FORKLIFT TRAINING SIMULATOR

In this section, we describe the design of a VR forklift training simulator developed in this research as a prototype. We note that the project focused on creating a VR-based simulation environment in which safety guidelines can be trained through interactive, reinforced learning based on feedback. The training content is scoped to only the essential forklift controls, including driving forwards/backwards, turning, changing gears, sounding the horn, controlling the forklift mast (up/down, left/right, tilt).

3.1. Training contents-'Scenarios'

In the training simulator, the user is shown a list of training Scenarios from which they can choose (Figure 1). Table 1 shows the list of Scenarios and the tasks included in each Scenario. The training program is designed so that the user can learn the most basic forklift operation skills progressively as they go through the Scenarios in sequence. Users are required to complete all tasks to complete a Scenario. Upon successful completion of a Scenario, the user is taken back to the main menu and can start any other Scenarios. The user can pause the training at any time and return to the main menu or restart the current task/Scenario at any point in the simulation.

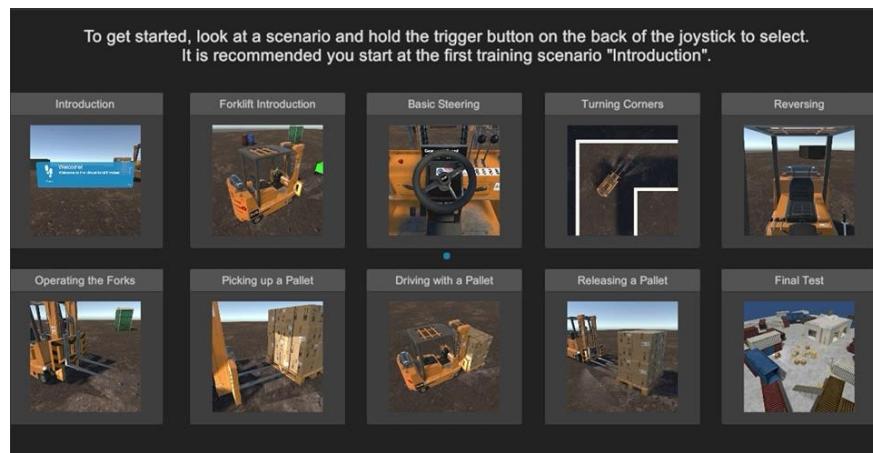


Figure 1. The Scenarios displayed in the main menu

Table 1. Training Scenarios

Scenario	Tasks included
Forklift Introduction Scenario	Changing forklift gears Driving forward Reversing
Basic Steering Scenario	Forward steering Backward steering
Turning Corners Scenario	Turning Corners Passing Intersections
Forklift Driving Test Scenario	Driving Turning Passing Intersection
Forks Introduction Scenario	Raising the forks Tilting the forks Shifting the forks Driving after moving the forks
Picking up a Pallet Scenario	Approaching a pallet Lifting the pallet
Driving with a Pallet Scenario	Driving with a pallet loaded Driving reverse with a pallet loaded
Releasing a Pallet Scenario	Releasing a pallet Backing away
Final Test Scenario	Comprehensive tasks combining all previous tasks

3.2. Feedback system

In each Scenario, except the Final Test, the user follows the instructions on how to operate a forklift safely and receives feedback messages on how they are performing. The system will constantly check the user's actions to ensure that they are complying with all safety guidelines embedded in the training program. If the system finds the user taking an unsafe action, an instantaneous warning or violation message is triggered, as shown in Figure 2. Specifically, thirteen different types of safety requirements were included in the design of the training program. These requirements were designed based on the safety guideline and requirements developed by SafeWork South Australia³ and US Occupational Safety and Health Administration⁴. Below is the description of how the safety requirements work in the simulation.

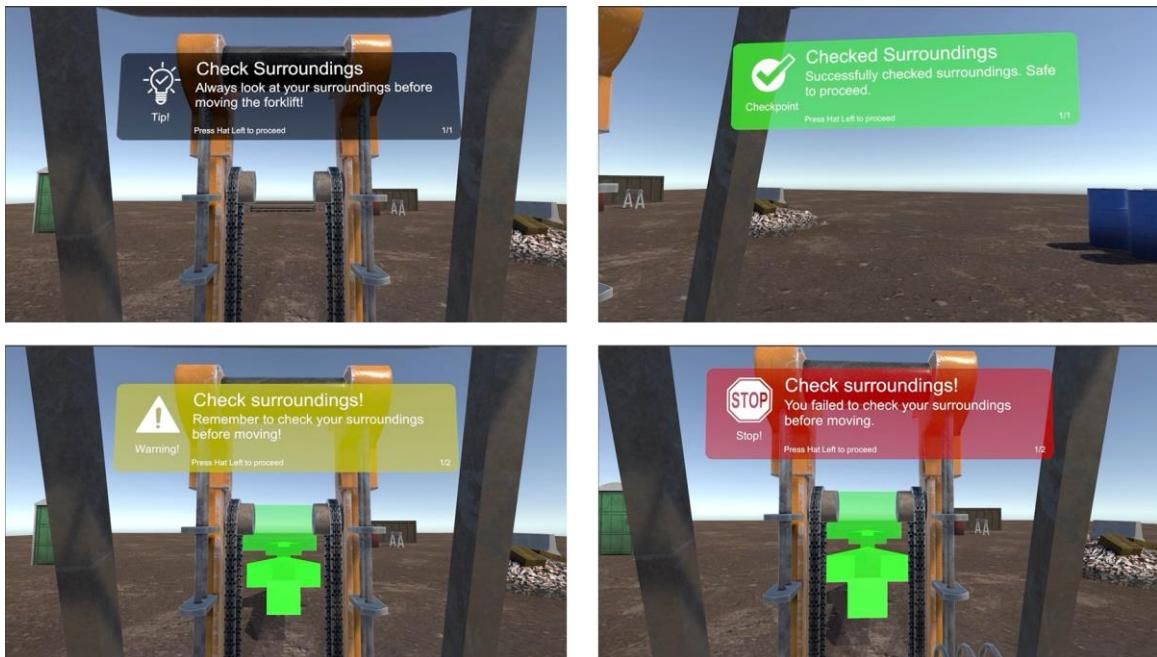


Figure 2. Various instruction and feedback messages generated in the simulator for interactive learning

Check Surroundings Before Driving. The system checks if the user checks the surroundings (by looking left and right) before driving the forklift. If the user stops driving for more than 10 seconds, they will need to check the surroundings again. The system warns the user if they start driving and have not checked their surroundings, and a violation is raised when the user continues to drive even after receiving the warning.

Drive Slowly. The system checks if the user is driving at a slow, safe speed. It warns the user if they are travelling at an unsafe speed (e.g., over 5 km/h). A violation is raised when the user exceeds the speed limit, which is set at 8 km/h.

Drive Smoothly. The system checks if the user is pressing down too fast or strongly on the accelerate or brake pedals. It warns the user if they have pressed a pedal too strongly over a set threshold.

Look in the Direction of Travel. The system checks if the user is looking in the direction of travel while the forklift is moving. It warns the user if they are not looking in the direction of travel while moving. A violation is raised if the user continues to look away from the direction of travel after warning.

Turn Wide. The system monitors if the user has performed a dangerously sharp turn. It warns the user if their turning angle is greater than the turning angle considered to be safe.

Sound Horn at Intersections. The system checks if the user has sounded the horn when approaching an intersection. It warns the user if they have forgotten to sound the horn. A violation is raised if the user ignores the warning and continues through the intersection.

³ <https://www.safework.sa.gov.au/sites/default/files/forkliftsafety.pdf?v=1527223033>

⁴ https://www.youtube.com/watch?v=VR2j3hIGs_o

No Operation of Forks while Moving. The system checks if the user is operating the forks while the forklift is moving. Operating the forks may be either raising, lowering, tilting, or shifting. It warns the user if they operate the forks while moving.

Load Pallet Correctly. The system checks that the pallet is correctly loaded onto the forks when the user attempts to lift a pallet. It warns the user if the pallet is not correctly loaded.

No Collision. The system checks if the forklift collides with any objects in the surrounding, e.g. walls or objects. A violation is raised if the forklift collides with anything in the environment.

Approach Pallet Safely. The system checks if the forklift has approached the pallet at a safe speed. A violation is raised if the forklift collides with the pallet at high speed.

Check Surroundings at Corner. When turning a corner, the user will be required to check both left and right. A violation is raised if the user drives passed a corner and has not checked both their left and right surroundings.

Check Pallet Secured. The system checks if the pallet is safely secured on the forklift. Fully secured means the forks are completely tilted back. It warns the user if they attempt to drive with a pallet when it is not fully secured.

Travel with Forks at Lowest Safe Height. The system checks if the user is driving with the forks at a safe height. Warns the user if they are driving and the forks are at an unsafe height.

4. IMPLEMENTATION

Based on the design described in the previous section, we implemented a prototype VR-based forklift simulator using commercial VR gaming devices. The prototype system used a desktop PC (CPU: Intel Core i7-7700k 4.20 GHz, RAM: 16GB, GPU: nVidia GTX 1070) running Windows 10 operating system for driving the VR simulation software and hardware. We used a Samsung Odyssey⁵ VR head-mounted display (1440x1600 resolution at 90Hz refresh rate and 110 degrees field of view) which provided immersive visualization and also tracked the user's head motion. A Logitech G920 Driving Force⁶ racing wheel and pedals were used as input devices for steering, accelerating, and braking the virtual forklift. The steering wheel also included buttons for sounding horn and changing gears. The system also used a Logitech Extreme 3D Pro⁷ joystick to mimic the levers to operate the forks (e.g., raise, lower, tilt, and shift) while a set of buttons on the joystick can also be used for responding to feedback messages (e.g., show next or previous message) or navigating in the system menu. Figure 3 shows the prototype system in use.

The training simulation software was developed using a Unity 2018.3.12f1⁸ 3D game engine and was organized into several modules. The Input module captures user input from the steering wheel, pedals, and the joystick, and feeds the input to the other modules, such as the Forklift module which simulates the movement and operation of a virtual forklift. The Scenario module defines and manages training scenarios. A Scenario consists of a list of training goals, tasks, safety rules, and messages which is progressed through as the user completes each task in the Scenario. While a Scenario is run, the Safety module checks if the user is following a certain safety practice required in the Scenario, and triggers feedback to the user as managed by the Feedback module.

⁵ <https://www.samsung.com/us/computing/hmd/windows-mixed-reality/hmd-odyssey-windows-mixed-reality-headset-xe800zba-hc1us/>

⁶ <https://www.logitechg.com/en-us/products/driving/driving-force-racing-wheel.html>

⁷ <https://www.logitechg.com/en-us/products/gamepads/extreme-3d-pro-joystick.html>

⁸ <http://unity.com>



Figure 3. VR Forklift Simulator prototype system setup. A user wears a VR head-mounted display while interacting with the simulation using a steering wheel, pedals, and a joystick

5. USER FEEDBACK

We collected user feedback through various demonstration events. The participants included both novice users and those with previous forklift operation experience. Several participants provided qualitative feedback after trialing one or two Scenarios. Most users found the simulator is easy to follow, and the driving wheel and pedal settings are intuitive. However, some users were shown to experience some difficulties with using the joystick controller to change gears, maneuver the forks or move in or out of the menus. We postulate that it is a limitation with using a single joystick to control various features, but not an issue with the design of training content or feedback system. In the user trials, it was observed that many users were initially not familiar with the safety requirement to check the surroundings prior to moving the forklift, but after some playtime, they automatically checked their surroundings before moving the forklift. This observation provided anecdotal evidence that the training system can quickly influence the user's safety behavior. Generally, the participants reported that they can clearly see the potential usefulness of the training approach, 'learning-by-doing' in the VR environment, especially for safe operation skills, because industrial safety has very much to do with how deeply internalized the safety guidelines are in one's habitual behavior.

6. CONCLUSIONS AND FUTURE WORK

We developed a prototype of VR-based forklift simulator that can enable safe operation skills training through an interactive feedback system. The training program consists of several modules to teach how to safely perform the basic tasks of forklift operation, such as driving, loading and unloading, following the safety guidelines. The system provides instantaneous instructions and feedback regarding safe operation. This training system is based on the model of "learning-by-doing". The user can repeat the training modules as many times as necessary before being able to perform the given task without violating any safety guidelines. A usability study conducted with a few forklift operators and several novice users provided preliminary evidence that the VR-based training system will be a useful and valid method for training basic safe operation skills, especially for inexperienced operators. For future work, we plan to conduct a formal user experiment to evaluate the prototype system, and we also plan to investigate further and extend the theme of VR-based safety training for other types of industrial skills.

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An Augmented Reality System for the Construction Industry and Its Impact on Workers' Situational Awareness

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Abstract: Augmented reality (AR) technology assists construction workers by superimposing additional virtual information onto their real worksite environments. Ideally, this provides them with a better understanding of their tasks and hence boosts task performance. However, the additional information that AR places in users' field of view could limit their ability to understand what is going on in their surroundings and to predict how conditions may change in the near future. AR-assisted systems on construction sites could therefore expose their users to safety risks due to disturbance from the system. Hence, it is important to understand how AR-assisted systems can block users' understanding of their immediate environments, and in turn, how worksite safety in the construction industry could be improved through better design of such systems. This preliminary research conducted a laboratory experiment that simulated rebar inspection tasks and compared the situational awareness of AR users against that of subjects using traditional paper-based inspection methods, as measured by the Situation Awareness Rating Technique. Based on the results, we discuss the safety impact of head-mounted AR-assisted displays on situational awareness during construction tasks.

Keywords: Augmented reality-assisted systems, Rebar inspection tasks, Paper-based inspection, Situational awareness, Situation Awareness Rating Technique

1. INTRODUCTION

Augmented reality (AR) enables the superimposition of information useful to task performance onto real-world scenes via diverse display systems including head-mounted displays (HMDs), desktop screens, and tablets [1]. It offers important benefits at various stages during construction projects, such as 3D visualization during a design phase, safety/inspection assistance during construction, and information access and evaluation for maintenance and renovation [2], contributing to better task performance [3]. For example, task-related information (e.g., drawings, 3D models, assembly instructions, etc.) that are overlaid on the user's field of view in the AR environment can reduce the frequency of attention-switching between tasks and such information, allowing practitioners to remain more focused on the task itself [4].

However, inserting additional information into users' field of view has been found to reduce their head and eye movement in real worksite environments [5]. Consequently, in some circumstances, AR interfaces could limit a user's ability to fully recognize the surrounding environmental conditions and/or to predict how the conditions could change in the near future. Since a construction site is a complex and dynamic environment, failure to maintain an appropriate level of situational awareness (SA) can have serious negative effects on worksite safety [6]. However, even though previous research efforts have developed various AR applications in construction, the negative impact of AR systems on safety has not been fully considered when designing the AR system.

As a starting point for such research, we conducted an experimental study comparing workers' SA between traditional paper-based and AR-assisted rebar-inspection tasks. Specifically, participants were divided into two groups who were asked to conduct rebar inspection tasks using a traditional paper-based and an AR-assisted inspection method, respectively. For SA measurement, we simulated these tasks in a construction site-like environment in a laboratory and used the Situation Awareness Rating Technique (SART) after the tasks were completed [7]. Based on the results, we discuss two groups' awareness of their surroundings by each SART category, i.e., understanding of the surrounding situation, attention supply, and attention demand.

2. LITERATURE REVIEW

2.1. AR-assisted tasks for construction

Applications of AR in construction projects have increased considerably in recent years [8], mainly because such technology can aid understanding of work processes through visualization of construction elements or task-specific information (e.g., drawings, instructions, etc.) against the background of actual project sites [9]. For example, a tablet-based system that visualizes 2D drawings has shown its usefulness to detect dimension errors on worksites more easily [10]. Recently, due to the advancement in mobile AR devices such as HMDs (e.g., Microsoft HoloLens), users can perceive an augmented environment continuously while leaving their hands free [5, 11]. This could provide additional benefits in construction contexts, in which a given individual will commonly engage in both cognitive (e.g., checking drawing information) and physical activities (e.g., fixing, assembling, etc.). Though previous studies have tended to focus on desktop-based or tablet-based AR applications in construction [10, 12], HMD-based ones would also seem to have considerable potential for use in diverse construction tasks.

2.2. Situational awareness and AR-assisted display systems

In general terms, SA is being aware of what is happening around us. More specifically, Endsley [13] defined it as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future." In the same work on SA theory, Endsley divided it into three levels, i.e., perception (level 1), integration and comprehension (level 2), and prediction (level 3).

In various complex and dynamic situations, a range of AR-assisted display systems are currently being used to support SA. In the security domain, for instance, an HMD-assisted display system is helping professionals to focus on the situation while keeping their hands free [14]. In ground transportation, AR-based systems can reduce drivers' distractions and thus increase their safety by boosting their understanding of the environment [15]. In aviation, AR-assisted head-up display systems enhance pilots' route awareness, such as through better understanding of their position within airports, distances to their next turns, and the directions of turns [16]. While these studies have found that the use of the AR system can enhance SA for the given task, one study [17] has reported that the additional information provided from the AR system and limited field of view may lead to users' failure of recognizing the surrounding conditions. This failure would have a negative impact on construction safety as construction workers should be continuously aware of safety risks at complex construction sites [18].

3. RESEARCH METHODOLOGY

To better understand how AR assistance could affect users' SA from a safety point of view, we selected rebar inspection tasks that involve intensive information processing within a short period and compared traditional paper-based and AR-assisted inspection tasks in a laboratory setting. Figure 1 represents an overview of the study procedure. First, we recruited a sample of 28 Ph.D. students (18 males, 10 females) from the Department of Building and Real Estate at the Hong Kong Polytechnic University. The participants were randomly divided into two groups of 14, one of which was assigned to paper-based inspection, and the other to AR-based inspection using a Microsoft HoloLens (A in Figure 1). Though the participants had various levels of professional experience in the construction industry, all were familiar with rebar inspection. To simulate a construction environment more realistically in the laboratory setting (B in Figure 1), recorded sounds of construction equipment were played at accurate volumes, and a person was employed to drive a laden forklift trolley near each

participant during the inspection task. The participants were asked to check for errors such as missing rebars, spacing issues, etc., in a sample of a rebar framework. While one group was given a paper-based rebar drawing during the inspection, the other was provided with 3D rebar drawing information superimposed on the actual rebar through HoloLens-based AR (C in Figure 1).

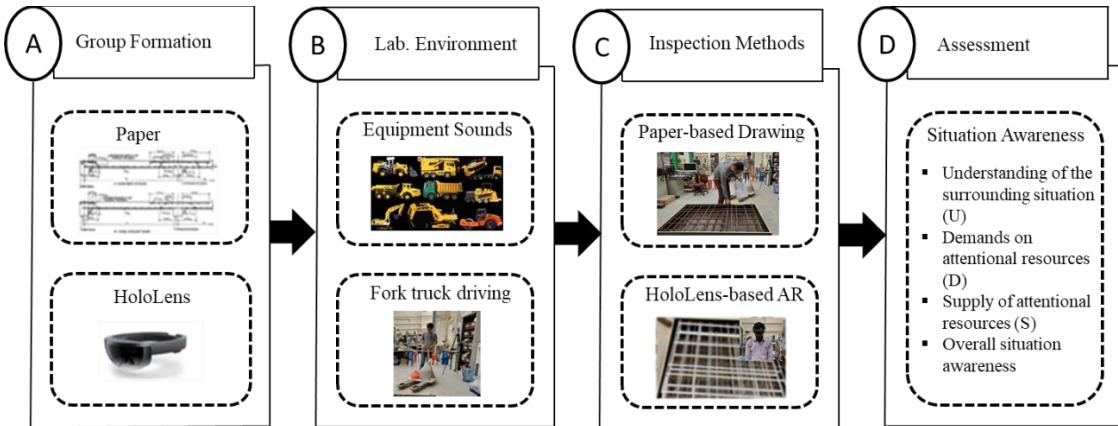


Figure 1. The framework of this research

In total, 14 errors were intentionally placed in the rebar framework, as shown in Figure 2. These fell into five general categories, i.e., 1) incorrect spacing between rebars ($n=5$), 2) extra rebars ($n=3$), 3) missing rebars ($n=2$), 4) insufficient rebar cover at the side face ($n=2$), and 5) insufficient rebar cover at the bottom face ($n=2$).

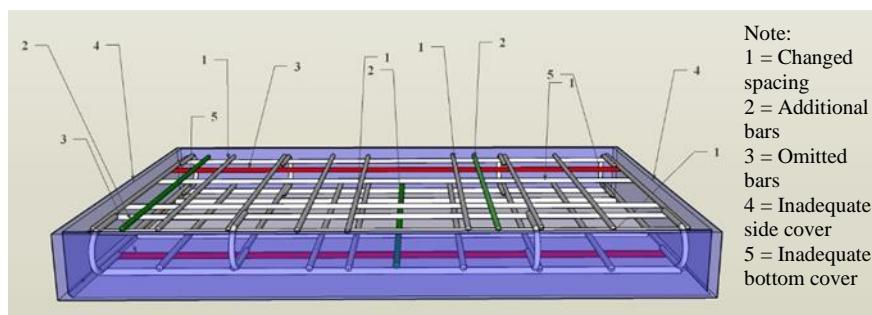


Figure 2. A conceptual diagram showing errors in a rebar framework

During the paper-based inspection session, participants were asked to find one error from each of the five above-mentioned classes by comparing the rebar drawing to the rebars actually placed in the slab formwork, as shown in Figure 3 (left). They were also allowed to use a tape measure, if necessary. Rather than being provided with a drawing, each member of the second group wore a Microsoft HoloLens showing a 3D rebar model superimposed on the actual rebars, as shown in Figure 3 (right). The 3D rebar model was initially drawn in SketchUp and then integrated with the HoloLens app Trimble Connect (<https://mixedreality.trimble.com/>) for registration. Participants in both groups were instructed to perform the inspection task as fast and accurately as possible while remaining aware of changes in the surrounding environment.

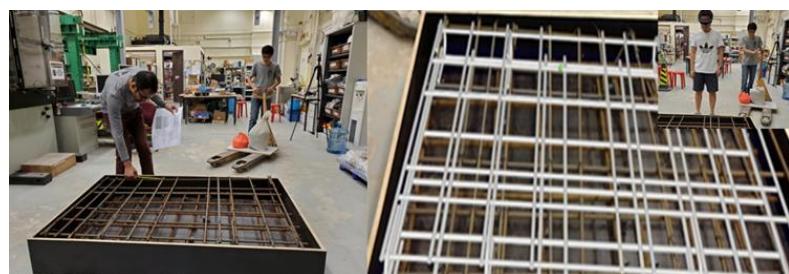


Figure 3. Paper-based and HoloLens-based AR inspection

For each session, we measured the participants' SA using SART [7] (D in Figure 1). The SART is a well-known post-trial subjective rating technique for the assessment of the participant's situation awareness. In this instrument, respondents self-report their SA based on 10 items, covering the surrounding environment's 1) information quantity, 2) information quality, 3) familiarity, 4) instability, 5) variability, and 6) complexity, and their own 7) arousal, 8) spare mental capacity, 9) concentration of attention and 10) division of attention. All items are answered using the same five-point Likert scale, ranging from 1 = Low to 5 = High. The 10 items are further grouped into three dimensions, i.e., understanding of the surrounding situation (U, items 1-3), demand on attention resources (D, items 4-6), and supply of attention resources (S, items 7-10); and a person's overall SART score is calculated as $SA = U - (D - S)$. Here "Understanding" (U) referring to understanding of the surrounding situation; "Demand" (D), represents the amount of attentional demand placed on surrounding environment; and "Supply" (S) referring to applied cognitive resources on surrounding situation.

4. RESULTS

Rebar-inspection accuracy for each experimental session was measured using one-way analysis of variance (ANOVA), the results of which are shown in Table 1, along with the mean number of errors identified by error type with their standard deviations (SDs); F statistics; and significance levels (p). On average, the non-AR-using participants identified more errors than the AR users did, with significant differences observed between the two participant groups when it came to identifying spacing, side-cover, and bottom-cover errors ($p < 0.05$). Also, a one-way ANOVA conducted on the data as a whole revealed statistically significant accuracy differences between the two inspection techniques ($p < 0.05$).

Table 1. Total number of errors correctly identified in each treatment

Rebar error type	Inspection medium	No. of errors placed	Mean no. of errors identified (SD)	F	p
Spacing between bars	Paper	5	3.64 (1.15)	7.44	0.01*
	HoloLens		2.35 (1.33)		
Extra rebars	Paper	3	2.35 (0.74)	0.32	0.57
	HoloLens		2.21 (0.57)		
Missing rebars	Paper	2	1.21 (0.80)	0.07	0.79
	HoloLens		1.28 (0.61)		
Side cover spacing	Paper	2	1.92 (0.26)	24.17	0.00*
	HoloLens		0.85 (0.77)		
Bottom cover spacing	Paper	2	1.07 (0.82)	19.11	0.00*
	HoloLens		0.00 (0.00)		
Total no. of errors identified	Paper	14	10.19 (3.77)	11.91	0.00*
	HoloLens	14	6.69 (3.28)		

Note. * = significant difference ($p < 0.05$).

Next, we used one-way ANOVA to examine the SART three main dimensions and overall SART scores within each treatment. As well as these overall scores with their cumulative mean values and SDs, Table 2 presents F statistics, and significance levels (p). For this purpose, first, we grouped SART 10 items into three main dimensions namely: (1) understanding of the surrounding situation or U (information quality, information quantity, familiarity); (2) the amount of attentional demand placed on surrounding environment or D (complexity, variability, instability); and (3) supply of cognitive resources on surrounding situation or S (arousal, concentration, division of attention, mental capacity). Then, by conducting one-way ANOVA test, we noticed significant inter-group differences in the three main SART categories ($p < 0.05$). The higher cumulative average score of (U) in the non-AR group (9.99) expresses that participants were more understanding of the surrounding situation than the AR users (8.76). The cumulative average values of (D) in the non-AR group (10.19) represent that the non-AR group was putting more attention to observe any changes in the surrounding environment than the AR users (9.48). And the cumulative average values of (S) in the non-AR group (13.40) indicates that participants of this group were used more cognitive resources on surrounding situation than AR users (11.37). After analysing cumulative mean group scores of SART three dimensions, a total SART score

is calculated by using the formula, $SA = \text{Understanding} - (\text{Demand} - \text{Supply})$. The overall cumulative mean SART score was found higher in the non-AR group (13.20) than for the AR-assisted group (10.55) which indicates that the non-AR group had higher SA; however, this difference was not statistically significant ($p > 0.05$). The following three subsections provide detailed discussions of each SART category in turn.

Table 2. Situation Awareness Rating Technique scores

SART category	Inspection medium	Mean (SD)	F	p
Understanding of the surrounding situation (U)	Paper	9.99 (2.69)	4.85	0.03*
	HoloLens	8.76 (2.38)		
Attention demand (D)	Paper	10.19 (2.13)	6.89	0.01*
	HoloLens	9.48 (2.27)		
Attention supply (S)	Paper	13.40 (3.72)	10.61	0.00*
	HoloLens	11.37 (3.22)		
Overall situation awareness (SA)= U-(D-S)	Paper	13.20 (4.28)	0.41	0.52
	HoloLens	10.55 (3.33)		

Note. * = significant difference ($p < 0.05$).

4.1. Understanding of the surrounding situation

Table 3 presents the SART scores for each subfactor of category U. There are no statistically significant differences between the two sessions, with all p values > 0.05 . However, a statistically significant difference was observed between two sessions for total understanding of the surrounding situation (information quality, information quantity, and familiarity). The cumulative mean values of total understanding of the surrounding situation were also observed higher in the non-AR group (9.99) than the AR users (8.76), which clearly indicates that non-AR group participants were more understanding of the surrounding situation.

Table 3. Situation Awareness Rating Technique scores for items on understanding of the surrounding situation

Subfactors of U	Inspection medium	Mean (SD)	F	p
Information quantity of the surrounding situation (U1)	Paper	3.42 (0.93)	2.35	0.14
	HoloLens	2.92 (0.82)		
Information quality of the surrounding situation (U2)	Paper	3.07 (0.82)	0.23	0.63
	HoloLens	2.92 (0.73)		
Familiarity with the surrounding situation (U3)	Paper	3.50 (0.94)	2.90	0.10
	HoloLens	2.92 (0.83)		
Total understanding of the surrounding situation = U = U1+U2+U3	Paper	9.99 (2.69)	4.85	0.03*
	HoloLens	8.76 (2.38)		

Note. * = significant difference ($p < 0.05$).

4.2. Demands on attentional resources

As Table 4 indicates, with regard to each subfactor of D, there was no statistically significant difference between the two sessions, with all p values > 0.05 . However, a statistically significant difference was observed between two sessions for total demand on attentional resources (instability, variability, and complexity). The cumulative mean value of total attention demand was also noticed higher in the non-AR participants (10.19) which denotes that non-AR participants were putting more attention to observe any changes in the surrounding environment than the AR users (9.48).

Table 4. Situation Awareness Rating Technique scores for items on attention demand

Subfactors of D	Inspection medium	Mean (SD)	F	p
Instability of the surrounding situation (D1)	Paper	3.42 (0.75)	0.60	0.44
	HoloLens	3.21(0.69)		
Variability of the surrounding situation (D2)	Paper	3.35 (0.74)	3.81	0.06
	HoloLens	2.78 (0.80)		
Complexity of the surrounding situation (D3)	Paper	3.42 (0.64)	2.48	0.12
	HoloLens	3.00 (0.78)		
Total attention demand = D = D1+D2+D3	Paper	10.19 (2.13)	6.39	0.01*
	HoloLens	9.48 (2.27)		

Note. * = significant difference ($p < 0.05$).

4.3. Supply of attentional resources

Table 5, which presents the SART scores for each of the four subfactors of S, shows that two of them – division of attention (S3) and spare mental capacity (S4) – differed significantly between two sessions ($p < 0.05$). There was also a statistically significant difference was observed between the two sessions for total supply of attentional resources (arousal, concentration, division of attention, and mental capacity). The higher cumulative mean value in the non-AR group (13.40) also indicates that participants of this group were used more cognitive resources on the surrounding situation than AR users (11.37).

Table 5. Situation Awareness Rating Technique scores for items on attentional supply

Subfactors of S	Inspection medium	Mean (SD)	F	p
Arousal (S1)	Paper	3.35 (0.74)	2.40	0.13
	HoloLens	2.85 (0.95)		
Concentration of attention (S2)	Paper	3.21(0.97)	0.17	0.68
	HoloLens	3.07 (0.82)		
Division of attention (S3)	Paper	3.42 (1.08)	5.44	0.02*
	HoloLens	2.64 (0.63)		
Spare mental capacity (S4)	Paper	3.42 (0.93)	4.57	0.04*
	HoloLens	2.71 (0.82)		
Total Attention Supply = S = S1+S2+S3+S4	Paper	13.40 (3.72)	10.61	0.00*
	HoloLens	11.37 (3.22)		

Note. * = significant difference ($p < 0.05$).

5. DISCUSSION

This study of SA across paper-based and AR-assisted rebar-inspection tasks has revealed that using the focal AR-assisted system led participants to understand their surroundings less well than a similar group that used traditional paper methods to complete the same task under the same conditions. The superimposed 3D rebar model shown in the head-mounted AR display system worn by the members of the former group appeared to help them to detect a certain kind of error, missing rebars. However, its disadvantage in terms of SA was observed across all three categories of the SART (U, D, and S); and the system could therefore be reasonably expected to increase potential worksite safety issues. Considering that inspectors on construction worksites perform several activities simultaneously – looking, comprehending, searching, remembering, and deciding – they are generally required to achieve full understandings of their surroundings over a very short period. Our experimental results confirm that equipping inspectors with head-mounted AR-assisted systems is likely to be unhelpful in such situations, as participants in the paper-based condition were more fully aware of small changes in the background environment than their AR-assisted counterparts were. In part, this could be explained by HoloLens' relatively small field of view, which would have tended to focus its wearers' attention more narrowly on their tasks than natural human vision would, and thus rendered them less alert to potential changes in their immediate environment.

6. CONCLUSIONS

Our findings have revealed that both the information provided in the display of an AR-assisted system, and that system's relatively restricted field of view, can negatively influence construction practitioners' SA, and thus would likely increase potential safety issues if used during worksite inspection tasks. However, a key limitation of this study that should be borne in mind before generalizing from its results is that it only looked at one type of AR-assisted system. Therefore, future research should examine the impacts on users' SA of others (e.g., tablet-based) AR-assisted display systems, especially those with better fields of view.

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Impact of the Fidelity of Interactive Devices on the Sense of Presence During IVR-based Construction Safety Training

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Abstract: Providing safety training to construction workers is essential to reduce safety accidents at the construction site. With the prosperity of visualization technologies, Immersive Virtual Reality (IVR) has been adopted for construction safety training by providing interactive learning experiences in a virtual environment. Previous research efforts on IVR-based training have found that the level of fidelity of interaction between real and virtual worlds is one of the important factors contributing to the sense of presence that would affect training performance. Various interactive devices that link activities between real and virtual worlds have been applied in IVR-based training, ranging from existing computer input devices (e.g., keyboard, mouse, joystick, etc.) to specially designed devices such as high-end VR simulators. However, the need for high-fidelity interactive devices may hinder the applicability of IVR-based training as they would be more expensive than IVR headsets. In this regard, this study aims to understand the impact of the level of fidelity of interactive devices in the sense of presence in a virtual environment and the training performance during IVR-based forklift safety training. We conducted a comparative study by recruiting sixty participants, splitting them into two groups, and then providing different interactive devices such as a keyboard for a low fidelity group and a steering wheel and pedals for a high-fidelity group. The results showed that there was no significant difference between the two groups in terms of the sense of presence and task performance. These results indicate that the use of low-fidelity interactive devices would be acceptable for IVR-based safety training as safety training focuses on delivering safety knowledge, and thus would be different from skill transferring training that may need more realistic interaction between real and virtual worlds.

Keywords: Immersive Virtual Reality (IVR); Interactive device; Presence; Task performance; Safety training

1. INTRODUCTION

The construction industry has suffered from a high rate of safety accidents at sites [1]. Accidents could occur when workers fail to recognize existing unsafe conditions, and thus safety training could provide safety-related knowledge to workers by improving their safety awareness [2]. Currently, traditional construction safety training methods such as paper-based teaching, videos, on-site training, and regular safety meetings such as safety orientations or toolbox meetings are commonly used [3]. Even though conventional safety training is now being commonly used to equip workers with safety knowledge, it has been considered passive due to the low level of engagement, limited acquisition and retention of knowledge [4]. In this regard, past studies have questioned the effectiveness of conventional safety training and pointed out that it was not an effective training method for construction workers [5,

6]. Recently, the use of virtual reality (VR) technology has gained its attention as an alternative way to provide safety training [7, 8]. VR-based safety training not only provides various simulated real working conditions without associated construction risks but also improves user's motivation and learning effectiveness [9, 10].

VR is an emerging technology that creates a computer-generated three-dimensional virtual environment with a high degree of realism and interactivity. Generally, a taxonomy of VR is based on three main components: autonomy (e.g., computational models and ability of processes to act and react to simulated events), interaction (e.g., a software architecture of the human-machine interface in the virtual environment system), and presence (e.g., the fidelity of available sensory input and output channels.) [11]. In particular, presence is one of the major contributing factors that could affect performance in VR environment [12, 13]. It refers to a mental state in which a user feels physically present within the computer-mediated environment [14]. It is related to the subjective experience of being in one place or environment, even when one is physically situated in another [15], or in other words: the sense of "being there" [2]. Research [13] indicates a higher sense of presence is linked with higher scores of performance metrics such as completing speed, errors, and quality in VR-based training [13]. This is consistent with the results from Salzman et al. and Lee et al. [16, 17] that indicated a better sense of presence in a virtual environment could enhance user's learning.

The hardware of VR systems consists of display devices such as Head-Mounted Display (HMD) and other interactive devices for user-VR system interaction. Previous research efforts have found that the fidelity of VR interactive devices has a significant impact on the level of presence by creating more natural control [18, 19] and easier operation [20]. VR-based interactive devices ranging from a simple hand-held controller to a real-like simulator, such as a steering wheel [21] and omnidirectional treadmills [22]. Although several authors have pointed out the importance of sense of presence in the virtual environment, the impact of different levels of fidelity of interactive devices has not been fully studied. Furthermore, even though some devices such as real-like simulators can provide high fidelity of interaction between users and the VR environment, their high price would obstruct the applicability of VR systems in practice. In this regard, cost-effective control systems may need to be developed by understanding how the fidelity of interactive devices would affect the sense of presence and training performance.

This study conducted the experiment with sixty participants to compare the fidelity of two different interactive devices by evaluating the sense of presence and training performance during the VR-based forklift operation. This research would identify whether low fidelity devices such as keyboard would significantly affect IVR-training experience, compared with high fidelity devices (steering wheel and pedals). The Presence Questionnaire [15] was used to find out whether the level of presence would create a significant difference between low-fidelity and high-fidelity groups during VR forklift training sessions. Based on the results, we discussed a method to improve the sense of presence in a cost-effective way.

2. LITERATURE REVIEW

2.1. IVR-based Training

Since the early 21st century, the latest visualization techniques are continuously adopting in various fields, and virtual reality (VR) has been proved to be an effective tool for furnishing people with a better learning environment and experience [9]. In general, VR platforms can be categorized into three paradigms based on the level of immersion: 1) non-immersive system, e.g., hand-held based VR and desktop-based VR; 2) semi-immersive system, e.g., stereoscopic 3D glasses and CAVE; 3) fully immersive system, e.g., VR HMD. Notably, the first prototype of a fully IVR system (Oculus Rift) was proposed by the Kickstarter project [22], which is currently one of the most prevalent and affordable high-quality VR headsets in the market.

IVR, with its fully immersive technology, can easily build up a space isolated from the outside world, contributing to maintain trainees' attention and concentration and may help trainees to acquire three-dimension knowledge. Research studies [23, 24] showed evidence that IVR-based training model for enhancing fire evacuee safety has been proved to be effective [23, 24]. Also, Ceenu et al [25] illustrated that instructor representation had a counterproductive relationship with the performance in a memory task and an object finding task in IVR. In construction, IVR-based training has been applied for hazard identification, skill learning and workforce training by benefiting from HMD gears with an affordable price and technological advancement in visual rendering [26, 27]. Diego-Mas et al. and Barkokebas et

al. tested HMD-based VR training to investigate its application in avoiding ergonomic risks and acquisition of maintenance skills [28, 29]. Their studies highlighted the effectiveness of such training approach on increasing perception of the ergonomics risks among workers and exploring the complexity of the task in IVR.

2.2. Factors Affecting the Sense of Presence in VR

Even though IVR-based training has been widely proposed in various fields, few studies have done that investigates how IVR systems would affect users' training experiences. However, there have been many studies for non-immersive VR such as Desktop-VR systems, providing a theoretical background on IVR-based studies. In general, factors that affect the sense of presence in VR systems can be categorized into hardware, VR contents, and user characteristics [30, 31]. According to Anthes et al. [22], VR hardware includes both input and output devices. Output devices refer to head-mounted devices, haptic devices and multi-sensory devices while input devices are interactive devices between real and VR environments such as driving wheels, controllers, navigation devices, body tracking, gesture tracking etc. The sense of presence in a VR environment can be measured by several hardware related parameters such as field of view, image quality, refresh rate, sound quality, tracking level, sensory isolation, haptic fidelity and force feedback [32].

Previous studies were conducted with different interactive devices for measuring the sense of presence. Hoffman et al. [33] found output devices such as HMD of 60-degree field-of-view can provide a higher level of presence by attracting attention as a result of reducing pain as well as having greater fun during the pain stimulus compared to the 35-degree VR group. Balakrishnan & Sundar [34] found that an interactive joystick with greater degrees of steering motion could enhance the sense of presence while navigating and searching for clues in a virtual office environment. In addition, it has been found that takeover quality only improved when user practices with steering wheel and pedals comparing to the game controller in IVR environment in a highly automatic car-driving task [21]. However, existing studies focus more on how internal parameters of output devices affect the sense of presence, especially spotlighting on HMD. Input devices are one part of the VR systems, understanding how they make contributions to the sense of presence and performance in VR environment is relatively important. Therefore, our study investigates how different fidelity level of input interactive devices influence the sense of presence and task performance in IVR-based training.

3. METHOD

To achieve this research study's objective, participants were recruited and randomly divided into two groups with low-fidelity (keybord) and high fidelity (a steering wheel and pedals) interactive devices for performing the forklift operation tasks. To provide a fully immersive environment, all the participants were equipped with a head-mounted display VR device. All of them were required to complete four forklift-operation tasks (basic introduction about forklift, steering a forklift, operating a fork, picking up a pallet) in the IVR environment. After completing the experiment, they filled out the Presence Questionnaire [15] for mensuring the level of presence. The finishing time of all four tasks was also recorded for comparing the task performance between two groups. Based on the previous literature review, we brought up the following assumptions:

H0:

Different VR interactive devices have different sense of presence;

High-fidelity devices have higher sense of presence;

The high-fidelity device group has a better performance (shorter task completion time).

3.1. Participants

A pilot study with two participants was conducted to provide a formative evaluation of the procedures and instruments. A total of 60 graduate students (57% of male, 43% of female) were recruited from the Faculty of Construction and Environment at the Hong Kong Polytechnic University and were randomly divided into two equal groups. Participants ranged in age from 20 to 40. All of the participants had heard about virtual reality, while 25% of total respondents had used VR-based applications or devices before.

3.2. VR System

Technical features. The forklift training scenario used in the study was developed using Unity 3D (version 2018.3.12f1), and all the participants wore a Samsung HMD Odyssey Plus (shown in Figure

1). The display resolution of this HMD was 1440×1600 per eye covered approximately 110° field of vision, refresh rate was 90 Hz and it also comes with a dual array MICs built-in headphone with AKG brand. These apparatuses provide users with an isolated, immersive and wide-field virtual environment.

In the low-fidelity IVR group, participants were provided a keyboard for forklift driving and a joystick for manipulating the fork. While in the high-fidelity VR group, the keyboard was replaced by a steering wheel and pedals that are similar with real forklift operating gears, as shown in Figure 1. Both groups performed the same training tasks in the same IVR environment.



Figure 1. Devices Used in The Experiment

Training contents. Firstly, all participants were taking basic knowledge about forklift operations to familiarize themselves with forklift operations in a virtual environment. Then, they were performing the different forklift operation tasks (e.g., steering a forklift, operating a fork, picking up a pallet, etc.) that were designed to provide task-based safety knowledge during forklift operations through interactive feedback. For example, while they performed a specific task such as moving forward, safety instructions were shown on the screen, and if they didn't follow the instructions, the system gave an alarm to users in the virtual environment. The training sessions include representative forklift-related tasks such as driving forward and backward, loading and unloading a pallet using a fork, etc.

3.3. Measurement

Subjective questionnaires are the most commonly used method to measure the sense of presence [35]. There are a few prevailing questionnaires in measuring presence, according to the number of citations in the Google Scholars database, the top five questionnaires are: Witmer & Singer 1998 [15] (no of citations, 5088), Schubert et al. 2001[36] (no of citations, 1232), Lessiter et al. 2001[37] (no of citations, 1085), Usoh et al. 2000 [38] (no of citations, 704) and Slater [39] (no of citations 628). To check the sense of presence with different VR interactive devices used in this study, the Presence Questionnaire (PQ) [15] (as shown in Table 1) of Witmer & Singer 1998 (WS) was adopted in this experiment. Witmer & Singer used factors based on the premier issue of Presence: Teleoperators and Virtual Environments and integrated them into the presence questionnaire (PQ). PQ includes four major factors: (1) control factors, (2) sensory factors, (3) distraction factors and (4) realism factors [15] and consists of 32 items using a five-point Likert-type scale. The degrees are “Very low” “low” “Medium” “High” and “Very high” corresponding to 1 through 5, respectively.

Table 1. Presence Questionnaire (PQ) [15]

Group Factors	Item Stems
CF	<p>How much were you able to control events?</p> <p>How responsive was the environment to actions that you initiated (or performed)?</p> <p>How natural did your interactions with the environment scene?</p> <p>How well could you actively survey or search the virtual environment using the device (e.g: wheel, joystick)?</p> <p>How proficient in moving and interacting with the virtual environment did you feel in the experiment?</p> <p>How much did the control devices interfere with the performance of assigned tasks or with other activities?</p> <p>How easy was it to identify objects through physical interaction, like touching an object?</p> <p>How easily did you adjust to the control devices used to interact with the virtual environment?</p> <p>How natural was the mechanism which controlled movement through the environment?</p>

SF	<p>How much did the visual aspects of the environment involve you?</p> <p>How much did the auditory aspects of the environment involve you?</p> <p>How compelling was your sense of objects moving through space?</p> <p>How completely were you able to actively survey or search the environment using vision?</p> <p>How compelling was your sense of moving around inside the virtual environment?</p> <p>How involved were you in the virtual environment experience?</p> <p>How much delay did you experience between your actions and expected outcomes?</p> <p>How quickly did you adjust to the virtual environment experience?</p> <p>How completely were your senses engaged in this experience?</p> <p>How much did your experiences in the virtual environment seem consistent with your real-world experiences?</p> <p>Was the information provided through different senses in the virtual environment (e.g., vision, hearing, touch) consistent?</p>
DF	<p>Were you able to anticipate what would happen next in response to the actions that you performed?</p> <p>How well could you concentrate on the assigned tasks or required activities rather than on the mechanisms used to perform those tasks or activities?</p> <p>To what extent did events occurring outside the virtual environment distract from your experience in the virtual environment?</p> <p>Were you involved in the experimental task to the extent that you lost track of time?</p> <p>How much did you focus on using the display and control devices instead of the virtual experience and experimental tasks?</p> <p>Were there moments during the virtual environment experience when you felt completely focused on the task or environment?</p>
RF	<p>How well could you identify sounds?</p> <p>How well could you localize sounds?</p> <p>How closely were you able to examine objects?</p> <p>How well could you examine objects from multiple viewpoints?</p> <p>How well could you move or manipulate objects in the virtual environment?</p> <p>How much did the visual display quality interfere or distract you from performing assigned tasks or required activities?</p>

Note. CF = Control Factors, SF = Sensory Factors, DF = Distraction Factors, RF = Realism Factors.

3.4. Procedure

First, participants were randomly allocated to the Low-fidelity IVR (LF-IVR, n=30) and High-fidelity IVR (HF-IVR, n=30) forklift training . Then each participant was filled a consent form and was briefed about this IVR experimental session. Before entering into the IVR environment, we further explained to participants how to use the joystick to navigate inside it and how they can use the other devices keyboard or steering wheel and pedals to interact with the training tasks. We then adjusted the HMD to the head of each participant and calibrated the pupil distance and volume for the best visual and audio effects. The participants were told that they would be further help on condition that they encountered any problems or they could not perform some movements in experiencing in the virtual environment. In the next step, participants were immersed into virtual world and finished the designated four tasks (basic introduction about forklift, steering a forklift, operating a fork, picking up a pallet) one by one in this sequence. On average time spent by each participant was approximately 26 min. After completing all these training tasks, participants were asked to finish the Presence Questionnaire [15] through an online platform outside the IVR environment. All questions displayed online were presented in a counterbalanced order to prevent any sequence effects.

4. RESULTS

There are two categories of metrics, one is the score in Presence Questionnaire, which will be compared with groups of factors referring to Control Factors (CF), Sensory Factors (SF), Distraction Factors (DF) and Realism Factors (RF) described by Witmer and Singer [15], another is finishing time in IVR tasks between two experimental conditions as the measurement of participants' performance. Before analyzing the data in detail, the first internal consistency of all questionnaires was checked using

Cronbach's alpha. Cronbach's alpha is a measure to check the internal consistency and reliability of the data. The consistency calculated by SPSS was found excellent in both experimental conditions(LF-IVR group: $\alpha = 0.930$, HF-IVR group: $\alpha = 0.900$). These alpha values indicate that the data reliability quality is high and can be used for further analysis. Then, the Shapiro-Wilk test [40] was used to test the data normality. The p values of the participants' task completion time produce by this test were greater than 0.05, indicating that such data were normally distributed. Therefore, parametric analysis was applied on this data. The p values of the other four factors (CF, SF, DF, RF) produced by the Shapiro-Wilk test were 0.000, indicating that such data were not normally distributed. Therefore, non-parametric analysis was used for four factors's data analyses.

4.1. Presence Measurement

A non-parametric analysis method (Mann-Whitney U test) was conducted for the comparison between HF-IVR and LF-IVR groups. The difference in all the group factors was found non-significant. However, the mean values of each group factor in the HF-IVR group are higher than the LF-IVR group, as shown in Table 2. This may imply that a steering wheel, joystick and pedals can produce a higher sense of presence and can assist to experience high immersive environment.

Table 2. Results of the Presence Questionnaire

Group Factors	HF-IVR (M \pm SD)	LF-IVR (M \pm SD)	MannWhitney U	p
CF	3.608 \pm 0.564	3.470 \pm 0.517	382	0.313
SF	3.810 \pm 0.390	3.673 \pm 0.578	407.5	0.528
DF	3.494 \pm 0.400	3.466 \pm 0.466	434	0.811
RF	3.605 \pm 0.527	3.573 \pm 0.531	447.5	0.970

Note: * $p < 0.05$ ** $p < 0.01$

4.2. Participants' Performance

For normal distribution of participants' performance, an independent t-test was conducted to the metric of time. No statistically significant difference was observed in task completion time between two groups, LF-IVR group (Mean \pm SD=26.13 \pm 7.77) and HF-IVR (26.30 \pm 7.69), $p = 0.934 > 0.05$. Nevertheless, in Linear Regression analysis, the regression coefficient value of CF was -6.541 ($t=-2.180$, $p=0.034 < 0.05$), which means that CF had a significant negative influence on time while the other three group factors were not significant (as shown in Table 3). This may imply partially that less time was required to complete the tasks with more advanced apparatus.

Table 3. The Linear Relationship between Time Performance and Group Factors

Group Factors	Coefficients	t	p
CF	-6.541	-2.18	0.034*
SF	3.924	1.126	0.265
DF	-4.510	-1.684	0.098
RF	1.660	0.696	0.490

Note: * $p < 0.05$, ** $p < 0.01$

5. DISCUSSION

This study examines how different types of interactive devices (LF-IVR, HF-IVR) affect the sense of presence and task performance in IVR-based forklift training environment.

5.1. Impact of Interactive device on the sense of presence

The first hypothesis regarding that different interactive devices have different degrees of presence couldn't find enough supporting materials in this study. 31 PQ items were not significant except for the

second question ($p = 0.044 < 0.05$) in PQ, which refers to "How responsive was the environment to actions that you initiated (or performed)?" From this point of view, HF-IVR with steering wheel and pedals provided participants with a better reactive action experience. This seems to be a sign of good interaction with the virtual world. However, that is a small part of the virtual reality interaction; others like control, naturalness and richness are not reflected at all. Of course, it is undeniable that mean scores in HF-IVR are commonly higher than LF-IVR, this might suggest high interactive devices would have a little improvement but not a decisive role in presence.

It is worth noting that the fidelity of the scene or virtual environment in IVR is relatively high and is akin to reality by offering a good field of view(110 degrees) and real auditory of site construction. Thus it could provide a high sense of the presence of real construction worksite. What's more, the contents in IVR training environment mainly focused on gaining forklift operations knowledge rather than real forklift operation tasks, and the tasks were relatively simple compared to some complex operation training, such as aviation training. These may impair the effect of interactive devices on inducing presence in this forklift training. Comparing the different fidelity of the scene with these two interactive devices would be the next step in the future study.

5.2. Effect of Presence on Performance

The results partially support the third hypothesis, showing that there was no remarkable difference of task execution time between the HF-IVR (26.30min) and the LF-IVR (26.13min) group, or even that the mean time is almost identical. However, the linear relationship was found significant between time and CF (Control Factors) with a negative value of -6.541. Other group factors were also correlated with time, but the coefficients were not significant. Fully presence may mean all kind of factors show a significant relationship to the task or the scene. Research study [41] delved into the various components of immersion that benefit VR, noting that full immersion are not indispensable [41]. This is in line with Bailey and Grassini [13, 42], who emphasized that high presence would be detrimental to the cognitive process and memory. It is under proven that full immersion is not necessary indeed. Based on this study, we can make a assumption that different tasks require different levels of presence, or specific presence. For example, we provided interactive equipments in addition to the IVR environment, which corresponded to Control Factors from Witmer and Singer questionnaires. Therefore Control Factors were significantly correlated with task performance. Thus, the function of different factors are based on the scene and we could not add up all the factors diluting the effect of the main ones.

5.3. Limitations and Future Directions

Considering several limiting factors, the results of this study need to be interpreted. A few participants complained that the fourth task (pick up the pallet) did not provide enough sight of view that they had difficulty in putting the fork inside the pallet. Later we found out that it was the problem of sitting-place adjustment. This inevitably gave rise to the problem of external interference. WS presence questionnaire is the method to observe presence in this study, but the individual question within the grouping factors are self-divided. This may cause some measuring error because of the classification. Nevertheless, we made sure that the grouping and order of the online questionnaires were consistent.

Future experiments are expected to fill up the questionnaire inside the VR headset. Completion of questionnaire forms outside the IVR may cause inconsistency and may depend on the individual's memory. Although this study used the most prevailing presence questionnaire, there are many ways to measure presence except the subjective questionnaire method (such as heart rate, eye data, skin conductor, etc.), which can be considered in future research.

6. CONCLUSION

Although past research studies have examined presence in various domains, few studies have been carried out on safety training and the effect of presence on behavior in VR. With the maturity of visual technology, more and more head-mounted displays (HMD) appear and the fully immersive virtual reality (IVR) shows an increasing trend with affordable price. However, IVR has not been widely applied as a low-cost solution in safety training. In this study, we developed an IVR environment of forklift training and explored how two types of interactive devices (low-fidelity IVR, high-fidelity IVR) affected the sense of presence and task performance in the fully immersive virtual environment. Then we compared presence factors and time performance between two groups. Our findings contribute to safety training performance in IVR with a better understanding of the sense of presence in several ways.

First, the high interactive device made little difference in presence compared to low interactive equipment which would help us to choose an inexpensive apparatus. Second, time performance in four tasks between the two groups were found almost no difference. Third, different parts of presence factors contributed to impacting time performance with different input or output devices. Based on these findings, further research may attempt to explore more factors affecting presence to better understand the relationship with immersive virtual reality-based safety training.

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VI. BIM-ENABLED AEC APPLICATIONS II (B3)

Smart-tracking Systems Development with QR-Code and 4D-BIM for Progress Monitoring of a Steel-plant Blast-furnace Revamping Project in Korea

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Abstract: Blast furnace revamping in steel industry is one of the most important work to complete the complicated equipment within a short period of time based on the interfaces of various types of work. P company has planned to build a Smart Tracking System based on the wireless tag system with the aim of complying with the construction period and reducing costs, ahead of the revamping of blast furnace scheduled for construction in February next year. It combines the detailed design data with the wireless recognition technology to grasp the stage status of design, storage and installation. Then, it graphically displays the location information of each member in relation to the plan and the actual status in connection with Building Information Modeling (BIM) 4D Simulation. QR Code is used as a wireless tag in order to check the receiving status of core equipment considering the characteristics of each item. Then, DB in server system is built, status information is input. By implementing BIM 4D Simulation data using DELMIA, the information on location and status is provided. As a feature of the S/W function, a function for confirming the items will be added to the cellular phone screen in order to improve the accuracy of tagging of the items. Accuracy also increases by simultaneous processing of storage and location tagging. The most significant effect of building this system is to minimize errors in construction by preventing erroneous operation of members. This system will be very useful for overall project management because the information about the position and progress of each critical item can be visualized in real time. It could be eventually lead to cost reduction of project management.

Key words: wireless tracking system, blast furnace revamping, BIM 4D

1. INTRODUCTION

It is expected that the loss due to the increase of the construction period in various projects in Korea arises since the problems of shortening working hours, the aging of construction worker and the shortage of skilled workers. It also applies to the blast furnace revamping project. The steel plant is composed of various sectors such as machinery, electricity, and instrumentation, and is complicatedly entangled with various companies and workers. Therefore, if changes occur in the design and construction process, it takes a lot of time and money to fix and rework. As a solution to this problem, many IT technologies are applied to construction sites. Typically, BIM technology integrates data in the design-procurement-construction-maintenance phase to enhance data consistency. In this study,

BIM technology is linked with the smart tracking system, so that the state of materials can be grasped in real time. It allows workers to be able to check the readiness of the material and adjust the work schedule accordingly. In order to establish the smart tracking system, QR code is assigned to each material and the user of the system inputs the status of the material in the order of unstoreng-warehousing-open storage-install-measurement-installation completion. Status of materials is automatically displayed in 3D and 4D models as color so that the manager can easily grasp the current situation. In addition, in open storage status, the user is allowed to enter a location of material so that the material can be easily found in the site. The research method is as follows. First, existing management system is analyzed in recent research. In order to take into consideration the specificity of the revamping project of blast furnace, wireless system is built based on the requirements of related experts. Some functions of the 3D experience of Dassault Systemes are modified to visualize the information collected by the wireless system. A pilot test is performed on the developed contents, and a smart tracking system is applied to a part of the site after correcting the problem through the pilot test.

2. ANALYSIS OF EXISTING SYSTEMS

QR code is a widely used technology from manufacturing, distribution, and logistics to marketing. The order information can be converted into QR codes and used for ordering and inspection work. QR codes can be attached to product labels to collect sales information and used for inventory management. By establishing a distribution history system, consumers can quickly look up the history of their purchases through QR codes. In this way, QR code helps users to know the information about the product or order without mistake [1]. These characteristics of QR code show that it can be used in construction management. QR code contains information about worker and work procedure so that the workers can quickly inquire related information. The information on the worker includes the company to which the worker belongs, whether the safety training is completed, and the scope of the approved work. Such data can be attached to the operator's helmet in the form of a QR code so that the user can inquire related information immediately when it is needed. With regard to work procedures, it is also possible to improve the user's convenience by attaching a QR code which allows the user to access the online work procedure on-site without having to carry the relevant documents with each work [2]. From the viewpoint of logistics management, it is easy to find a case where RFID is applied mainly in a construction site [3]. However, RFID has a disadvantage in that the price of each tag is high and must be read through a specific device. On the other hand, the tag cost of QR code is cheaper than RFID tag and it can be utilized on the smart phone which many workers already have [1]. Therefore, this study aims to suggest a method to utilize QR code for material tracking system of revamping project.

3. BLAST-FURNACE SMART TRACKING SYSTEM

3.1. System configuration and development architecture

The overall structure of the system presented in this study is shown in Figure 1. First, in a wireless system, a QR code is attached to an item to be managed. It is distributed to the supplier and attached to the item at the time of shipment. The smartphone scans the QR code attached to each item and accesses the website where the user can enter the status of the item. The status of the item means the preparation state of the item divided into the stages of unstoreng-warehousing-open storage-install-measurement-installation completion. The user selects the status of the item on the website. Then, the status data of the item is stored in the interface table DB.

The BIM platform reflects the status data received through the wireless system in 3D and 4D information. The BIM platform DB is an existing DB that contains 3D and 4D information about the revamping project. In this DB, the 3D model and 4D data are handled through CATIA and DELMIA of Dassault Systemes, respectively. In this research, 3D and 4D information is utilized to visualize the status data obtained through the wireless system in color and to quickly grasp the supply situation of the item. Therefore, the status data of the interface table is updated to the BIM platform DB. Some functions of CATIA and DELMIA are modified to display status data in color.

To operate the system in this process, the interface table must have the tag data and the 3D data of the

items to be managed. This is because the status data input by the user should be matched with the tag data and the 3D data of the item whose status is changed should be transmitted to the BIM platform DB. To do so, the tag data must be assigned to the 3D model at the time of 3D model production, and this must be transmitted to the interface table. However, in this project, Matching 3D data and tag data are carried out additionally in consideration of the introduction of smart tracking system during the project ongoing.

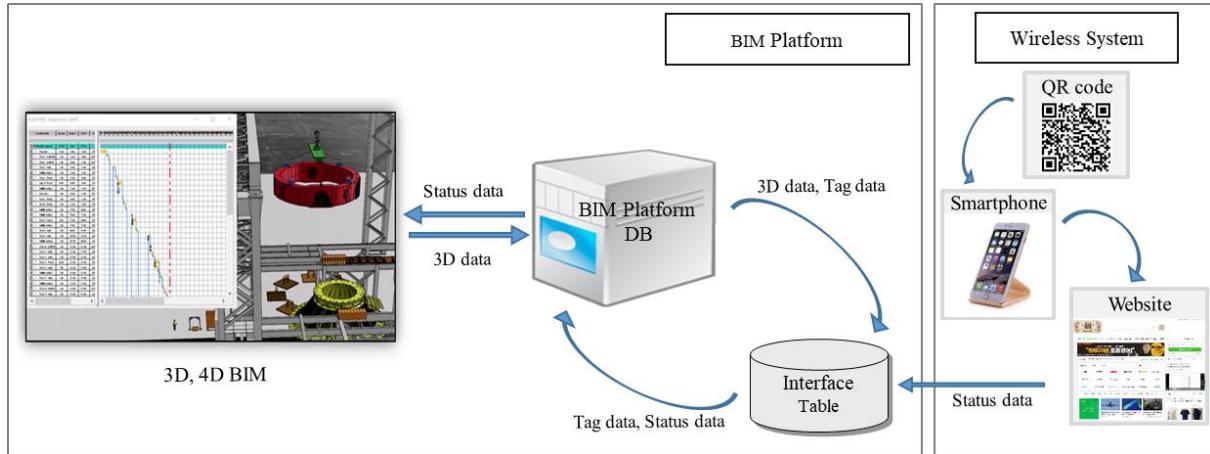


Figure 1. System configuration

3.2. Development of the wireless system

The development of the wireless system proceeds as shown in Figure 2. First, in the requirements collection and analysis, the user of the system and the material management process reflecting the characteristics of the revamping project are determined. Based on this process, the configuration of the screen of website to be accessed by the user is determined. In the data modeling stage, the entities to be managed and the relationship between entities based on the user's requirement is established, and the attributes and the format of them are defined.

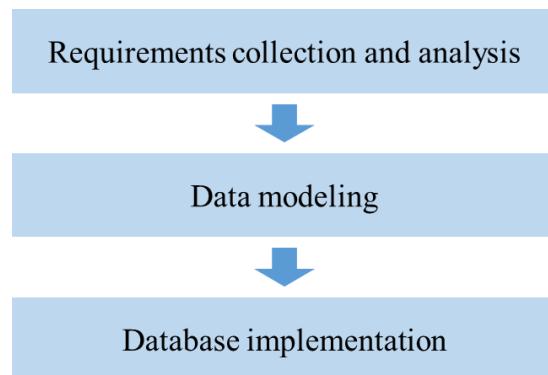


Figure 2. Wireless system development procedure

3.2.1. Requirements collection and analysis

The main user of the system to be developed is P company which manages the revamping project, and the contractor who performs the project. The main page of website designed to reflect these requirements is shown in Figure 3.

MAIN IRON THROUGH BODY

Project Info
Construction period ('19.05 ~ '20.05)

Proj Name	Contractor	Manager		Picture
		P	Contractor	
3Line	P	Hong 010-0000-0000	Lee 010-0000-0000	

Equip. Info

Class No	Dwg. No	Count	Weight	Supply Flag
3250	123-23-123	1 / 3	15.5t	PE

Supplier Info

Suppliers	Packing. No	Manager
====	123-23-123	Jung 000-0000-0000

Unstoring Warehousing Open Storage
Install Measurement Installation completion

[Search](#) [Exit](#)

Figure 3. Main page of website

The main page is accessed immediately when the user scans the QR code. Therefore, the main page includes information about the item to which the QR code is attached and information about the supplier. The picture function enables the supplier to retrieve the picture of the item to be uploaded by the supplier. The contact information of representatives of P company and the supplier of each item is included in the page so that the user can immediately contact them when necessary. At the bottom of the page, the statuses for the item input by the user are listed. Considering the user's work process, this is divided into 6 statuses (unstoring-warehousing-open storage-install-measurement-installation completion) in total. Unstoring means the time when the supplier starts the transportation. Therefore, entering the unstoring status and uploading of the picture of the item are functions that the supplier connects to the system and uses. After the items arrive at the site where the revamping project is performed, the item becomes a warehousing state. Open storage refers to a status in which items are stored in a designated place before installation. Install means that the item is placed in where the item should be located. When the inspection is performed, the item becomes the measurement status and when all the work is finally completed, the item becomes the installation completion status.

Some processes are added to the main page based on the requirements to improve user convenience and prevent errors. First, the search function is added so that the main page can be accessed without the QR code. This corresponds to Figure 4 (a). If the QR code attached to the item is located in a place that is difficult to scan or is damaged, the user can access the main page by inputting tag code or item name manually. This function is also needed to download the QR code that the supplier attaches to the item, as shown in Figure 4 (b). In the open storage status, the user can further input the location of the item, thereby preventing the item from being lost in the site. The page for entering the location is shown in Figure 4 (c).

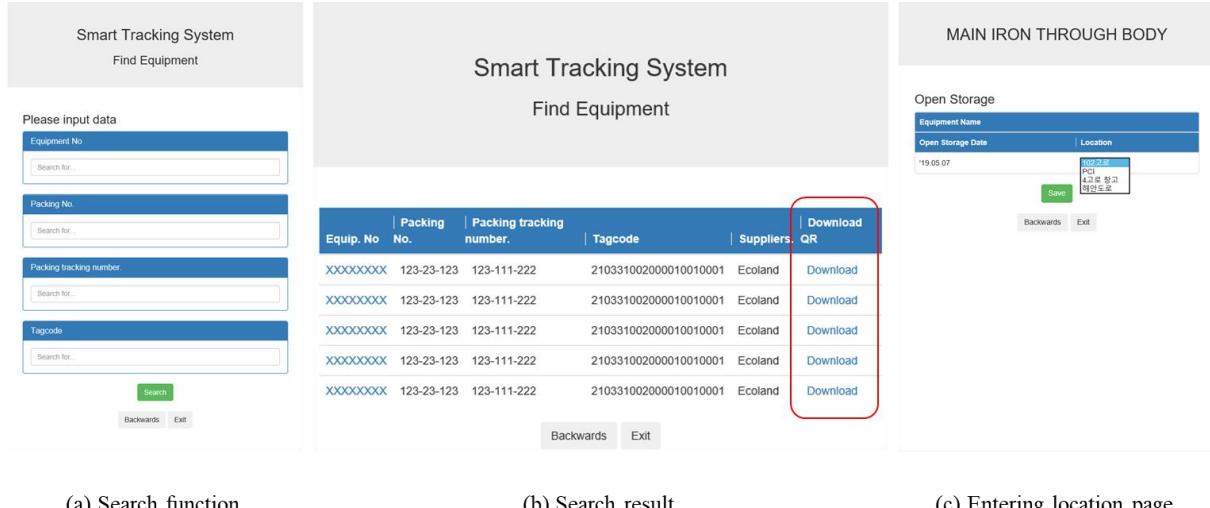


Figure 4. Additional functions

3.2.2. Data modeling

The data and its format required to configure the database are defined based on the pages in requirements collection and analysis. First, the necessary data are listed in Table 1. Project information is about the revamping project. The contact number is used to reach the person in charge of P company and contractor. Equipment information is about the individual item to be managed to which the QR code is attached. The packing tracking number and the drawing number are listed so that the user can check other reference documents. The information such as count, weight, and picture of item help the user to check whether the item matches the order in the process of confirming the item. Status information includes the status of each item and the date to show its past history.

Table 1. Required data list

Division	Data	
Project information	Project period	Contact number of P company
	Project name	Contact number of contractor
	Contractor	
Equipment information	Item name	Count
	Picture of item	Weight
	Packing tracking number	Supply flag
	Tag code	Supplier name
	Class number	Packing number
	Drawing number	Contact number of supplier
Status information	Unstoring date	Install status
	Unstroring status	Installation location
	Warehousing date	Measurement date
	Warehousing status	Measurement status
	Open storage date	Installation completion date
	Storage location	Installation completion status
	Install date	Install status

The main entities derived from the above data are project, equipment and contractor. For security reasons, the user entity is added as the range of the user is limited. Figure 5 shows the structure of attribute and relationship according to entity.

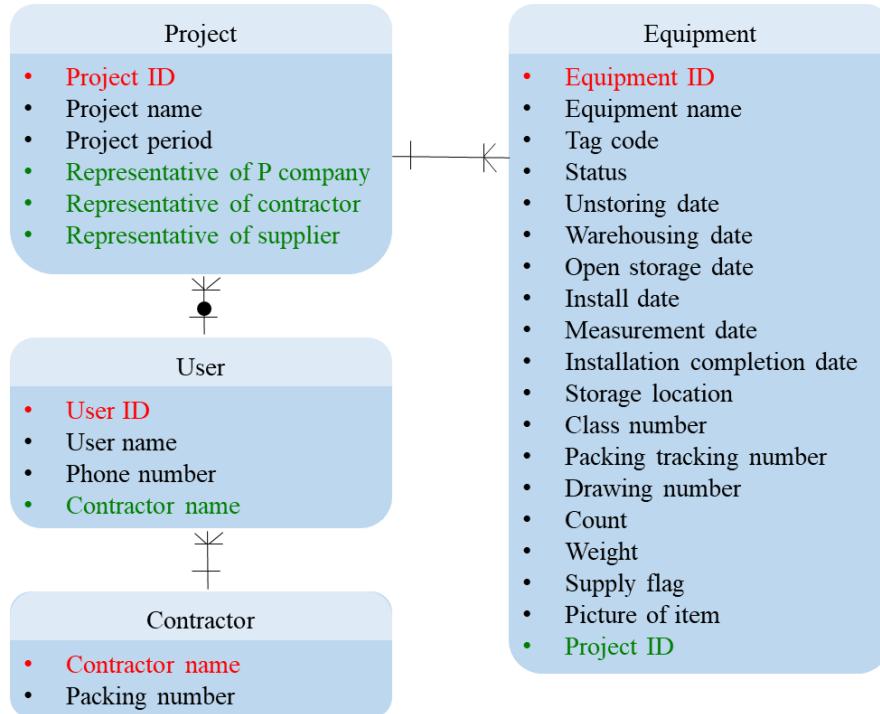


Figure 5. E-R diagram

The red attribute means the primary key, and the green attribute means the foreign key. The interface table is implemented based on E-R diagram of Figure 5.

3.3. Visualization of item status using BIM

Status information about the items collected in the interface table through the wireless system is periodically uploaded to the existing BIM platform DB. The BIM platform DB contains the 3D model and the process order of the facilities that are subject to the revamping project. This platform is based on the 3D experience of the Dassault Systeme. Based on 3D experience, various applications of Dassault Systeme such as CATIA, DELMIA and ENOVIA are utilized. In this study, smart tracking system are integrated with 3D and 4D data so that users can grasp information about several items easily. Therefore, it is necessary to change the status information uploaded to BIM platform DB into color. To do this, the B.I essential functions supported by the 3D experience application are utilized. B.I essentials is an abbreviation for business intelligence essentials, which helps users to identify important information easily [4]. B.I essential function allows 3D model to be displayed in pre-specified colors according to each stage of unstoring-warehousing-open storage-install-measurement-installation completion. In order to connect the status information of each item and the 3D model, the tag data used for specifying the item in the smart tracking system and the 3D model of the item in the BIM platform DB should be connected. The recommended process is to generate tag code according to the agreed numbering rule when creating the 3D model and give it the 3D model in advance. This is because tag codes can be assigned to many 3D model objects without looking for items to manage. However, since the revamping project was carried out prior to the research, assigning the tag code to the inherent code of the 3D model is performed. A list of 3D models is extracted first and the tag data is linked to the list by experts. The list is imported into the interface table as a final step. Experts who are familiar with the equipment is necessary to perform this task in order to specify a 3D model.

4. PILOT TEST AND ON-SITE APPLICATION

In order to verify the developed contents through the above process and collect points to be improved, a pilot test is performed by a unit test method. Based on the results of pilot tests, wireless systems and visualization are improved. The issues to be considered for the system to be applied in the site are also examined in advance.

4.1. Pilot tests

For the pilot test, a smartphone, PC used typically and a license for 3D experience were needed. To be used as a test target, facility completed in 3D modeling were separated into 13 parts arbitrarily. Tag codes and status scenario were assigned to each of 13 parts. The pilot test verified whether each function in the webpage works properly, whether it was easy to use on both smartphones and PCs and whether the color of the 3D model changed according to the status information. Table 2 is the check list used in the pilot test.

Table 2. Check list

Division	Description
Wireless system	Connection via QR code
	Direct connection not through QR code
	Check of Item search result
	Entering status information according to scenario and check of result
	Functionality of main page
Visualization	Display of status information of items in 3D model
	Check of location information of item in 3D model
	Display of status information of items in 4D model

As a result of the pilot test, it is confirmed that the functions that were originally intended in the wireless system operated correctly. Visualization of status information also performed well for applications in 3D experience. But some drawbacks were pointed out. First, all of the buttons for entering status information are activated. For example, when the item is in the warehousing status, the unstore button is unnecessary. Therefore, unnecessary button should be disabled to prevent users from making errors. It was also pointed out that information indicating the current status of the item did not exist in the main page. In order to know the current status and location of the item, the user must press the status button. So, a table will be added to show the relevant information directly on the main page.

4.2. On-site applications

After resolving the problems that raised through the pilot test, the on-site application proceeds. In on-site application, hundreds of items are targeted unlike the pilot test which targets 13 items. The smart tracking system is first applied partially to find out the problem of enlargement application in advance. The on-site application will be done through the following process. First, the item to be managed is selected from all the items of the revamping project. When it comes to item to be managed, it is required to set the level of detail of the item. When an item is managed either in an excessively small unit or a large unit, it is difficult for the user to grasp the current situation of each item. The QR code is distributed to the supplier of the item to be managed and a tag containing the QR code is attached to each item. In this case, the attachment method should be selected in such a manner that it can be maintained for a management period in consideration of characteristics such as the size, usage method and the surrounding environment of each item. Typically, a tag printed on paper is used because of a price advantage but for items placed in an extreme environment, the QR code marked by laser on the aluminum plate is used to prevent the tag from being dropped or damaged. Suppliers scan these tags at

the time of shipment and update the status of the items. Experts who have sufficient knowledge about each item connect 3D model to the tag data of the target items.

5. CONCLUSIONS AND FUTURE RESEARCH

The purpose of this study is to reduce the cost due to decrease of construction worker productivity and shortened working hours by introducing smart construction technology. The pilot test is completed so far and on-site application is in process. End users of smart tracking system showed positive response in the pilot test. It is targeted that application of the smart tracking system will be gradually introduced throughout the project until next year.

Projects for revamping blast furnaces tend to be repeated periodically and smart construction technology that is used recently has a trend to be standardized and packaged. The smart tracking system is also developed to be used in future projects. In the case of the 3D experience platform of Dassault Systeme for utilizing BIM information, however, paying a license fee is required. Therefore, introducing the system for small and medium-sized companies may be less cost-effective than large companies.

Since the system developed in this study constitutes a part of Advanced Work Package(AWP), it can be the basis for future project management techniques such as linkage with schedule or Earned Value Management System (EVMS).

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Concrete Reinforcement Modeling with IFC for Automated Rebar Fabrication

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Abstract: Automated rebar fabrication, which requires effective information exchange between model designers and fabricators, has brought the integration and interoperability of data from different sources to the notice of both academics and industry practitioners. Industry Foundation Classes (IFC) was one of the most commonly used data formats to represent the semantic information of prefabricated components in buildings, whereas the data format utilized by rebar fabrication machine is BundesVereinigung der Bausoftware (BVBS), which is a numerical data structure exchanging reinforcement information through ASCII encoded files. Seamless transformation between IFC and BVBS empowers the automated rebar fabrication and improve the construction productivity. In order to improve data interoperability between IFC and BVBS, this study presents an IFC extension based on the attributes required by automated rebar fabrication machines with the help of Information Delivery Manual (IDM) and Model View Definition (MVD). IDM is applied to describe and display the information needed for the design, construction and operation of projects, whereas MVD is a subset of IFC schema used to describe the automated rebar fabrication workflow. Firstly, with a rich pool of vocabularies practitioners, OmniClass is used in information exchange between IFC and BVBS, providing a hierarchy classification structure for reinforcing elements. Then, using International Framework for Dictionaries (IFD), the usage of each attribute is defined in a more consistent manner to assist the data mapping process. Besides, in order to address missing information within automated fabrication process, a schematic data mapping diagram has been made to deliver IFC information from BIM models to BVBS format for better data interoperability among different software agents. A case study based on the data mapping will be presented to demonstrate the proposed IFC extension and how it could assist/facilitate the information management.

Key words: Building Information Modeling, Construction Automation, Industry Foundation Class, Prefabrication, Steel Reinforcement

1. Introduction

Reinforced concrete (RC) has always been one of the most often used materials in buildings and occupies a large part of the total costs of the construction projects. In Hong Kong, other types of structure like steel-framed structure only occupy less than 2% of all construction costs.[1] In order to meet time-saving performance and avoid error-prone manual intervention, automated rebar fabrication is promoted by government and the construction industry due to limited space and high labor costs in construction sites especially in metropolitan urban regions like Hong Kong. Many innovative fabrication

technologies with larger freedom for designers could help to open the mass market of digital fabrication.[2]

The usage of Building Information Modeling (BIM) contributes to improving the quality and integrity of the automated rebar fabrication, for its capability to store information of building elements and facilitate the workflow of fabrication and procurement. [3,4] And 3D coordination view in BIM tools could help to maintain the consistency of rebar design and fabrication. But very few researches have been studied on the implementation of BIM platform to achieve more potential functions.[5] As one of the very few public and internationally recognized standards (ISO/PAS 16739:2005) for exchange of information in the Architecture, Engineering & Construction (AEC) domain[6], Industry Foundation Class (IFC) is one of the most used data formats, currently utilized to carry semantic information of reinforcement elements among multiple types of BIM-based software agents. IFC can provide most of the parameters needed for fabrication. Except for IFC, Omniclass, which is frequently used in facility management, could be utilized as well for its hierarchy classification structure for reinforcing elements. And the International Framework for Dictionaries (IFD) could offer a consistent definition for the usage of each specific attribute by assigning a Globally Unique Identifier (GUID) to each element.[7] Thus, it will be helpful if reinforcement information could be exchanged seamlessly from BIM-authoring software to the rebar cutting and bending machines through IFC.

Currently the data format adopted by most types of rebar machines is BundesVereinigung der Bausoftware (BVBS). It is a numerical data structure developed and readable for most types of fabrication machines to perform rebar cutting and bending, with reinforcement information stored and exchanged through ASCII encoded file. [3] The details of BVBS is introduced in the following section. However, not all attributes needed in BVBS could be found in IFC files of BIM models because it mainly focuses on geometrical and semantic information of two-dimensional rebars. Thus, it's necessary to ensure the smooth data format conversion and improve the interface which allows characters from different construction phases to collaborate with each other and perform data interoperability effectively.

This study aims to present an extended IFC schema to address and compensate for the missing information within the data conversion for better data interoperability. The software and data interoperability could promote the collaboration of different phases in the whole life cycle of construction to achieve certain functions like clash detection and BIM-based quantity take-off. [8] A schematic data mapping diagram is made to expose the relationship between them in order to achieve a more efficient data interoperability performance with the aid of Information Delivery Manual (IDM) and Model View Definition (MVD). And a use case is presented to illustrate the extended IFC schema.

2. Methodology

BIM has several open specifications such as IFC and openBIM standard which can assist the process to convey information. IFC carries the semantic information of reinforcing steel and is utilized to enhance the data interoperability among different software programs, whereas the data format recognized by rebar machines is BVBS. BVBS specification can be applied in Computer Numerical Control (CNC) bending machines or Production Planning and Scheduling (PPS) software[3], transferring data of reinforcement in cast-in-place concrete structures such as bar length, diameter, and steel grade. More details of BVBS data format are shown in Figure 1.

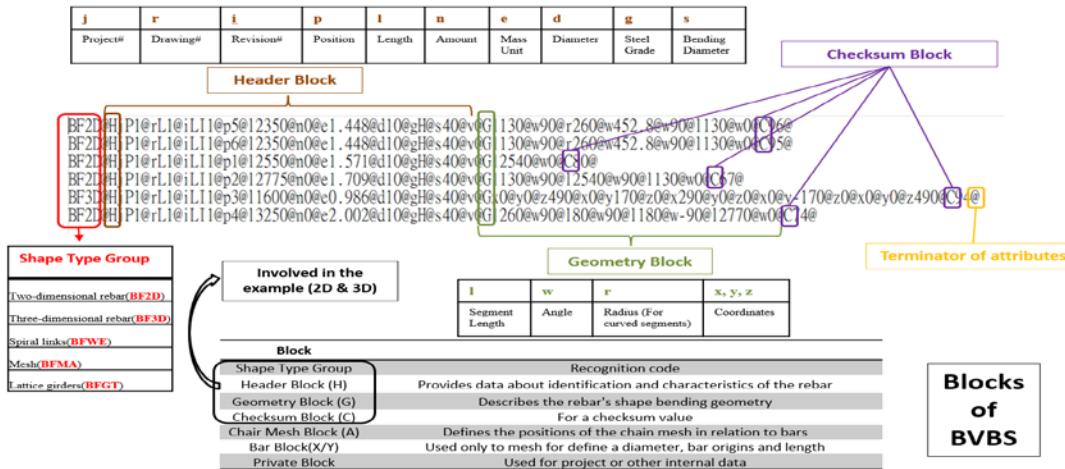


Figure 1. Details of BVBS data format

IDM is adopted to offer a reference database to reveal the information required by different processes in construction and execution[9], and to bring together various types of information into a single operating environment to reduce the repetition of paper documents. In this study, the information needed to be exchanged between BVBS and IFC is determined referred to IDM, and IFC entities related to key parameters of rebar are extracted and inspected within the process map, exchange requirements and function parts. MVD, a data-centric subset of the IFC schema, is applied to narrow down the broad scope of the overall IFC schema according to the required function, since not all phases in construction like design, procurement, fabrication and operation, need the same entities in each specific domain. In this study, rebar MVD, shown in Figure 2, is used to display and describe the data exchange process in the automated rebar fabrication workflow. Within the conversion from IFC to BVBS specification, data loss occurs and leads to mistakes in cutting and bending, making it necessary to conduct an extended IFC schema through parsing BVBS specification with the IFC schema of the most updated version so that newly added and removed entities or attributes will be considered to address missing information and improve the data interoperability. This extended IFC schema could cover more types of reinforcing elements than the existing one and provide enough information needed for fabrication.

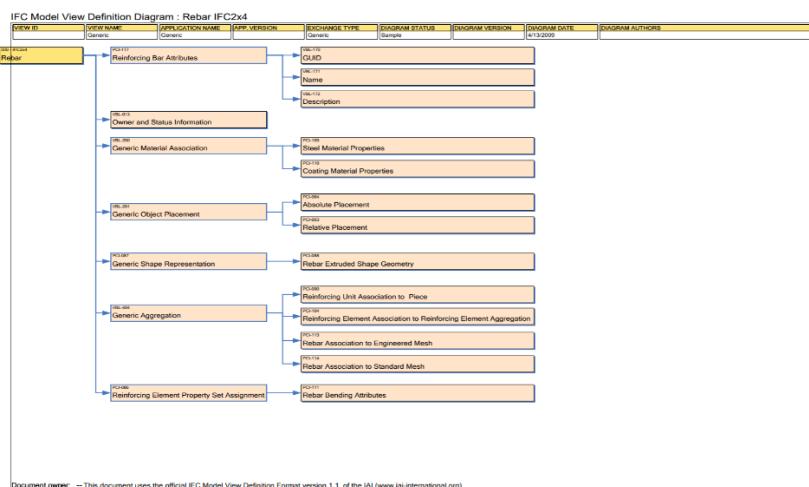


Figure 2. Rebar MVD [10]

3. Data mapping

Most of the BVBS-relevant information can be collected from IFC files according to IFC4Add2 (Version 4.0 Addendum 2) exported from authoring BIM software. Thus, a mapping chart (Figure 3) and a data mapping diagram (Figure 4) have been made in order to reveal the correlation between the two data sets more clearly and precisely.

BVBS		IFC4	
Attributes	Block	Entity	Entity
		IFC4Add2-TC1	
		Attributes	Attributes
Two-dimensional rebar(BF2D)	Shape Type Group recognition code		Mainly 2D rebars and Specific to Rebar Shapes
Three-dimensional rebar(BF3D)			Mainly 2D rebars and Specific to Rebar Shapes
Spiral links(BFWE)			
Mesh(BFMA)			
Lattice girders(BFGT)			
Project Number(j)			
Drawing Number(r)			
Revision Number Index(i)			
Position(p)			
Length(l)	Header Block (H): provides data about identification and characteristics of the rebar	IfcElement	Tag
Amount(n)		IfcReinforcingBarType	BarLength
Mass Unit(e)		IfcElementQuantity	Quantities
Diameter(d)		Derived from and Specific to Rebar Shape and Steel Grade	
Steel Grade(g)		IfcReinforcingBarType	NominalDiameter
Bending Diameter(s)		IfcReinforcingElementType	HasAssociation
Leg Length(l)		IfcReinforcingBarType	BendingParameters
Angle of Following Bend(w)		IfcReinforcingBarType	BendingParameters
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		

Figure 3. Data mapping between BVBS and IFC4

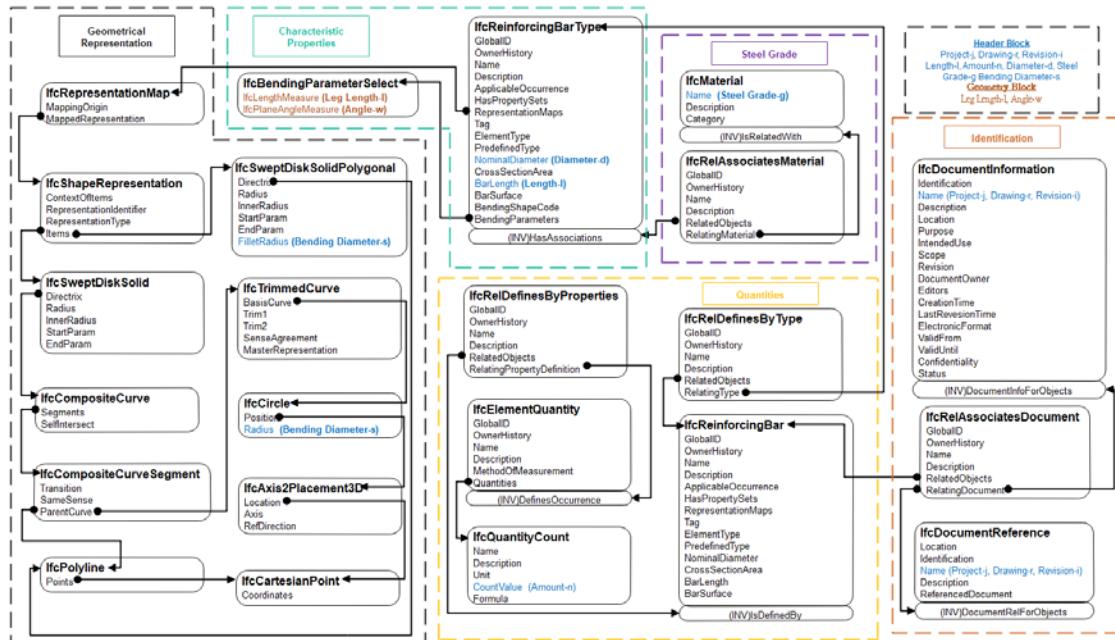


Figure 4. Schematic data mapping diagram between BVBS and IFC4Add2

3.1. Identification representation

Identification information is a vital element for fabricators to track and categorize rebars from different projects. There's no perfectly matched identification-related data in IFC that could be extracted for project number (j), drawing number (r) and revision index (i), as required in BVBS specification. In order to satisfy identification parameters in Header Block of BVBS, external documents could be involved to provide these data. Under this circumstance, the object level entity *IfcReinforcingBar* is linked with *IfcDocumentInformation* or *IfcDocumentReference* through *IfcRelAssociatesDocument*, and under either of these two entities, the corresponding number and index could be obtained through the attribute *Name*.

3.2. Geometrical representation

IfcSweptDiskSolid is one of the most used ways of constructing a three-dimensional solid, by sweeping along the directrix which can be defined by *IfcCompositeCurve*. This *IfcCompositeCurve* is composed of one or more *IfcCompositeCurveSegment* and they all originate from *IfcPolyline*, the end points are defined by the cartesian points assigned. And *IfcSweptDiskSolidPolygonal*, the subtype of

IfcSweptDiskSolid, is another method where the source of attribute directrix can only be *IfcPolyline*. In this way, an optional attribute *FilletRadius* under *IfcSweptDiskSolidPolygonal* could be applied to denote bending diameter in BVBS format.

3.3. Characteristic properties

Bar diameter and length are directly provided by attributes *NominalDiameter* and *BarLength* under *IfcReinforcingBarType*. In previous IFC schema before IFC4, there is no bending-related entities or attributes, but *BendingShapeCode*, and *BendingParameter* were added in this update to fill the gap.

BendingShapeCode indicates a shape code from some certain standard that can be referenced from *IfcDocumentReference* using external resources. Related to *BendingParameters*, *IfcBendingParameterSelect* can obtain the value of segment length and angle following bends, the specific description of which is defined by *BendingShapeCode*.

3.4. Quantities

There is no usable attribute under *IfcReinforcingBarType* or *IfcReinforcingBar* to define the amount of reinforcement, but we can deduce it from the number of reinforcement entities or acquire it from one quantity set named *Qto_ReinforcingElementBaseQuantities* which can measure count, length, and weight. Quantities of reinforcement can be offered as well by the attribute *CountValue* under *IfcQuantityCount*, the attributes of which could be inherited from *IfcElementQuantity*, the objectified relationship between *IfcReinforcingBar* and which could be indicated by *IfcRelDefinesByProperties*.

3.5. Steel grade

Steel grade was previously represented by attribute *SteelGrade* under *IfcReinforcingElement* but this attribute has been deprecated in the recent update. Instead, it can be provided in attribute *Name* under *IfcMaterial* which is associated with *IfcReinforcingElementType* by *IfcRelAssociatesMaterial*. And the parameter of strength such as Young's Modulus and Shear Modulus can be provided by the property sets for object template named *Pset_MaterialMechanical*. And we can obtain general properties like mass density from *Pset_MaterialCommon* as well so that we can calculate the mass unit required by BVBS specification accordingly.

4. Extension of IFC schema

4.1. Extended entities

Three out of five types of reinforcement shapes required by BVBS could be found in IFC: two-dimensional rebar (BF2D), three-dimensional rebar (BF3D) and reinforcing mesh (BFMA). Among them, represented only in Cartesian points, 3D rebar is special and hard to be distinguished, not to mention spiral links (BFWE) and lattice girders (BFGT), which are even harder to be defined. Therefore, it's necessary to propose new entities in type level for 3D rebar, spiral links and lattice girders.

The shape definition of 2D rebar is formed by *IfcPolyline* which could also be applied to three-dimensional solid. Thus, both 2D rebar and 3D rebar could share this entity but an identifier may be needed in the beginning to distinguish 3D from 2D. In terms of spiral links, the spacing of stirrups is one of the crucial parameters apart from basic ones like diameter and steel grade. Another essential one depends on the perimeter of the cross-section of building element: a circular one needs the radius; but for a square one, a side length will do. As for lattice girders, more distinctive attributes are utilized since it's a combination of bars at different locations. The diameter of the upper chord, lower chord and diagonal chord, length, pitch and height are all compulsory parameters required in prefabrication. The diagram of extended IFC entities is shown in Figure 5.

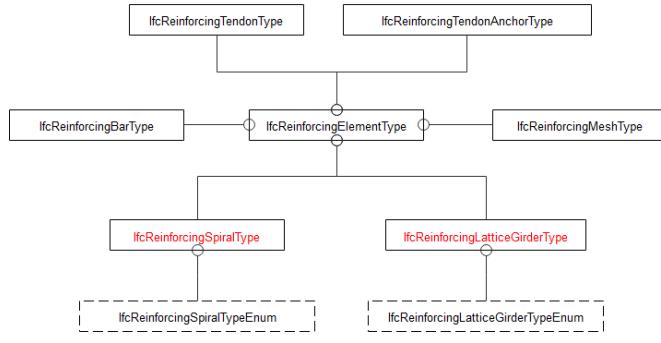


Figure 5. Express-G diagram for extended IFC entities

4.2. Extended parameters under existing entities

4.2.1. Mark Number

In response to the *Position* in BVBS format which can be regarded as bar mark in prefabrication, there is no perfectly fit attribute in reinforcement related IFC entities. There is a *Tag* attribute under entities in type-level. However, since one element type may be utilized in various locations in the same project, *Tag* in type-level may not be appropriate enough. An added *BarMark* attribute under entities in type-level like *IfcReinforcingBarType* and *IfcReinforcingMeshType* can fill this gap by marking those reinforcing elements which possess the same parameters in the same phase, making it more convenient to conduct prefabrication and transportation.

4.2.2. Mass Unit

The definition of mass unit of reinforcement is mass per item, and this should be a derived parameter, the acquisition of which involves calculation based on density, length, and diameter. However, there are no such attributes in IFC, making it more inconvenient to perform cost estimation and quantify reinforcement production, which is particularly essential to decision making and evaluation of the structural design. Thus, a new attribute *MassUnit*, the value of which can be obtained through arithmetic operations, is supposed to be appended in the current list of entities at type level like *IfcReinforcingBarType* instead of instance-level to avoid time wastage due to the increased size of models.

4.2.3. Hook Type

There are 5 separate hook types in Revit: two standard hooks 90 deg/180 deg, three stirrup/tie hooks 135deg/90 deg and stirrup/tie seismic hook 135deg. But there is no hook related IFC entities, and hooks are represented as segments and angles. For instance, the hooks are represented by *IfcCircle* plus *IfcPolyline*, which is not distinctive enough and the size of models will be enhanced, which is surely a wastage. Proposed attributes *HookAtStart* and *HookAtEnd* under type-level entities like *IfcReinforcingBarType* will make the entity simpler and more readable, saving storage space for IFC file as well.

5. Use case

Examples of the reinforcing bar information represented by the extended IFC are shown. The attributes (Figure 6 and 7) in *IfcReinforcingSpiralType* and *IfcReinforcingLatticeGirderType* are proposed according to the geometrical and semantic parameter as well as the attribute inheritance of *IfcReinforcingBarType* and *IfcReinforcingMeshType*. [11] Except for fixed attributes including *PredefinedType*, *BendingShapeCode* and *BendingParameters*, geometrical attributes are proposed corresponding to each type.

#	Attribute	Type
10	PredefinedType	IfcReinforcingSpiralTypeEnum
11	SpiralLength	IfcPositiveLengthMeasure
12	SpiralDiameter	IfcPositiveLengthMeasure
13	LongitudinalBarNominalDiameter	IfcPositiveLengthMeasure
14	TransverseBarNominalDiameter	IfcPositiveLengthMeasure
15	LongitudinalBarCrossSectionArea	IfcAreaMeasure
16	TransverseBarCrossSection	IfcAreaMeasure
17	Pitch	IfcPositiveLengthMeasure
18	BendingShapeCode	IfcLabel
19	BendingParameters	IfcBendingParameterSelect

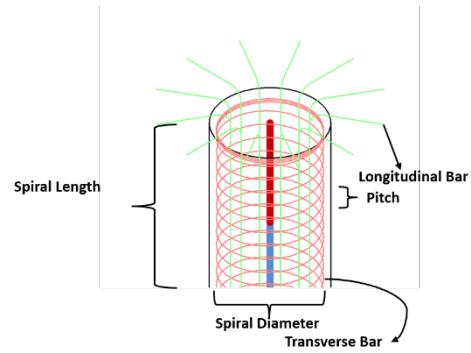


Figure 6. Proposed attributes of IfcReinforcingSpiralType with reference to IFC4Add2 Documentaion [12]

#	Attribute	Type
10	PredefinedType	IfcReinforcingLatticeGirderTypeEnum
11	UpperChordLength	IfcPositiveLengthMeasure
12	LowerChordLength	IfcPositiveLengthMeasure
13	DiagonalChordLength	IfcPositiveLengthMeasure
14	Width	IfcPositiveLengthMeasure
15	Height	IfcPositiveLengthMeasure
16	UpperChordDiameter	IfcPositiveLengthMeasure
17	LowerChordDiameter	IfcPositiveLengthMeasure
18	DiagonalChordDiameter	IfcPositiveLengthMeasure
19	UpperChordCrossSection	IfcAreaMeasure
20	LowerChordCrossSection	IfcAreaMeasure
21	DiagonalChordCrossSection	IfcAreaMeasure
22	Pitch	IfcPositiveLengthMeasure
23	BendingShapeCode	IfcLabel
24	BendingParameters	IfcBendingParameterSelect

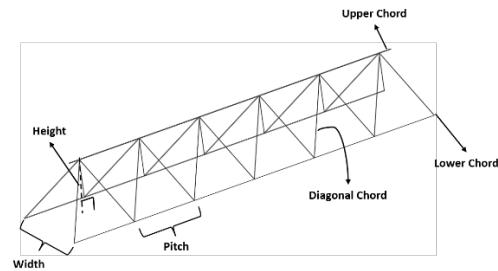


Figure 7. Proposed attributes of IfcReinforcingLatticeGirderType with reference to IFC4Add2 Documentaion [13]

Under *IfcReinforcingBarType*, four new attributes are added: *MarkNumber*, *MassUnit*, *HookAtStart*, and *HookAtEnd* (Figure 8). *MarkNumber* is used to indicate the serial number of rebars with the same parameters so that it will be easier to categorize and track them while converting them into BVBS file. Required by fabrication machines, *MassUnit* presents the mass per reinforcing bar. In terms of *HookAtStart* and *HookAtEnd*, the type is defined to be *IfcReinforcingBarHookTypeEnum*, under which there are five types of hooks: Standard 90, Standard 180, Stirrup/Tie 135, Stirrup/Tie 90 and Seismic 135. In the tree view of the IFC file (Figure 9), the attributes including extended ones are listed in the brackets after IFCREINFORCINGBARTYPE and added attributes are marked.

#	Attribute	Type
10	PredefinedType	IfcReinforcingBarTypeEnum
11	MarkNumber	IfcReal
12	NominalDiameter	IfcPositiveLengthMeasure
13	CrossSectionArea	IfcAreaMeasure
14	BarLength	IfcPositiveLengthMeasure
15	MassUnit	IfcPositiveLengthMeasure
16	BarSurface	IfcReinforcingBarSurfaceEnum
17	HookAtStart	IfcReinforcingBarHookTypeEnum
18	HookAtEnd	IfcReinforcingBarHookTypeEnum
19	BendingShapeCode	IfcLabel
20	BendingParameters	IfcBendingParameterSelect

Figure 8. Extended attributes in IfcReinforcingBarType [10]

```

#490=IFCENFORNCURBARYTYPE('0xGMB@X0!0$w!SSGI!#42,'Rebar Bar';#40 : Shape :00 :362889'-.#,$#394,#614:#465,$.JfcLabel
(UserDefinedType,'UserDefined',1',40,.00125663708143592,1071,592,36210,'FLAIN Standard_90,Solid/Title 135,IfcLabel(1BS8666),$);
#394=IFCEBEAM('0xGMB@X0!0$w!SSGI!#42,'Concrete',Rectangular,Can:400,Can:36000000,$.JfcLabel
#42=IFCNUMBERBRISTORY(#39,$.S.,NOCHANGE,$.S.,$156076627);
#39=IFCPERSONANDORGANIZATION(#36,$.S,$);
#5=IFCAPPLICATION(#1,'2020','Autodesk Revit 2020 (ENU)',`Revit');
#1=IFCORGANIZATION($,'Autodesk Revit 2020 (ENU)',`Revit');
#392=IFCLOCALPLACEMENT(#141,#391);
#141=IFCLOCALPLACEMENT(#33,#140);
#33=IFCLOCALPLACEMENT(#31295,#32);
#391=IFCAKSI2PLACEMENT3D(#389,$.S$);
#389=IFCARTESIANPOINT(0.,0.,-3000););
#385=IFCPRODUCTCONTAINER('2d:2mk_dibro',#388,$.S.,#383));
#614=IFCPROPERTYSETDEFINITION('2d:2mk_dibro',#388,$.S,$);
#42=IFCNUMBERBRISTORY(#39,$.S.,NOCHANGE,$.S,$.S.,$156076627);
#39=IFCPERSONANDORGANIZATION(#36,$.S,$);
#5=IFCAPPLICATION(#1,'2020','Autodesk Revit 2020 (ENU)',`Revit');
#1=IFCORGANIZATION($,'Autodesk Revit 2020 (ENU)',`Revit');
#465=IFCREPRESENTATIONMAP(#464,$.S$);
#464=IFCAKSI2PLACEMENT3D(#462,#22,#141);
#485=IFCHASEREPRESENTATION#105,'AdvancedSweptSolid',#484);
#105=IFCQEMETRICREPRESENTATIONSUBCONTEXT('Body','Model',*,*,*,#99,$.,MODEL_VIEW,$);
#484=IFCSWEPTDISKSOLID(#472,20.,$0.,.273,);

```

Figure 9. Tree view of example for extended IfcReinforcingBarType

6. Automatic BVBS Code Generation for Rebar Fabrication

Provided the extended IFC schema, this study further develops a customized program based on the common BIM-authoring software (i.e., Autodesk Revit 2020) for the automatic generation of BVBS. As Figure 10 shows, the program was developed using Dynamo (a Python-based visual programming tool). It starts by reading the semantic and geometric information of each individual rebar in the BIM model. Based on the schematic data mapping between IFC and BVBS, the program then extracts the fabrication-related information from the rebar BIM model to automatically generate the BVBS.

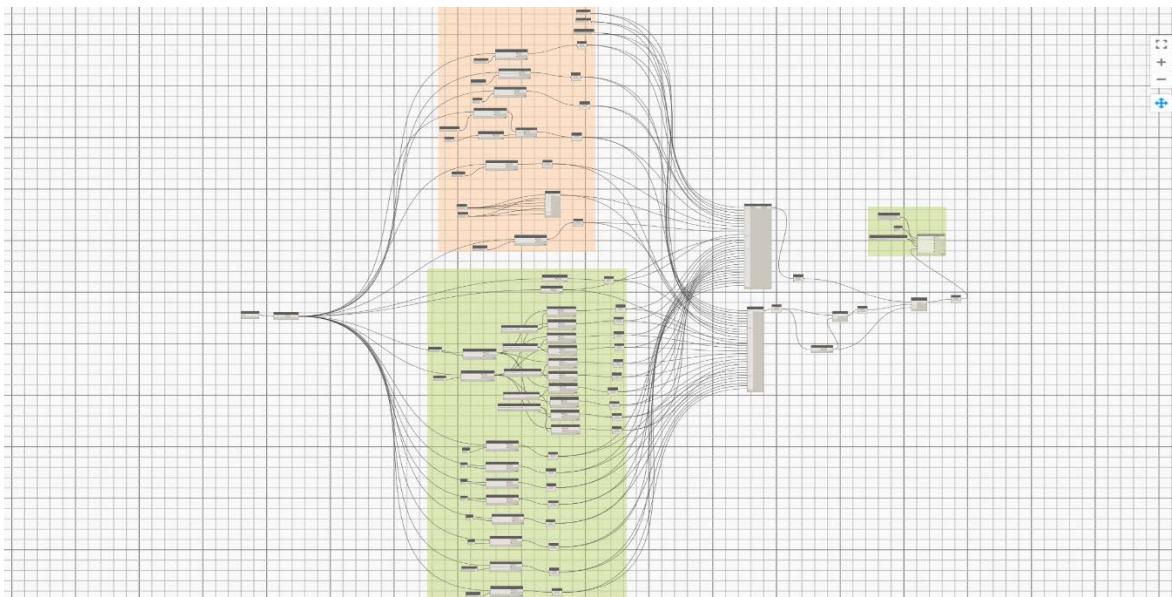


Figure 10. Overview of Dynamo program

So far, most of the attributes required in BVBS can be extracted from BIM models using the developed Dynamo program (by Python scripts customized by users). After the BIM model extraction, all required parameters in the Header Block can be acquired, except the project number, drawing number and revision index which need to be inputted manually according to practical situations. Regarding the geometry block, the team currently focuses on two-dimensional rebar. The program can provide the segment length in form of different capital letters that were assigned and customized in Revit-Rebar-Edit Family, and obtain the angle value through calculation based on Trigonometric function and segment length. The checksum block was also generated by the Dynamo program, the results of which could be utilized to check the correctness of BVBS string.

The circular column joint given by CIC (Figure 11) was built in Autodesk Revit to test and verify the proposed IFC extension and the Dynamo program. After selecting all the steel reinforcement of any element like beam and column in the BIM model, the Dynamo program can be executed to automatically generate an output file in Excel Spreadsheet. As Figure 12 shows, the Excel Spreadsheet contains all the detailed geometric and semantic information for the steel reinforcement in BVBS format of beam in the model.

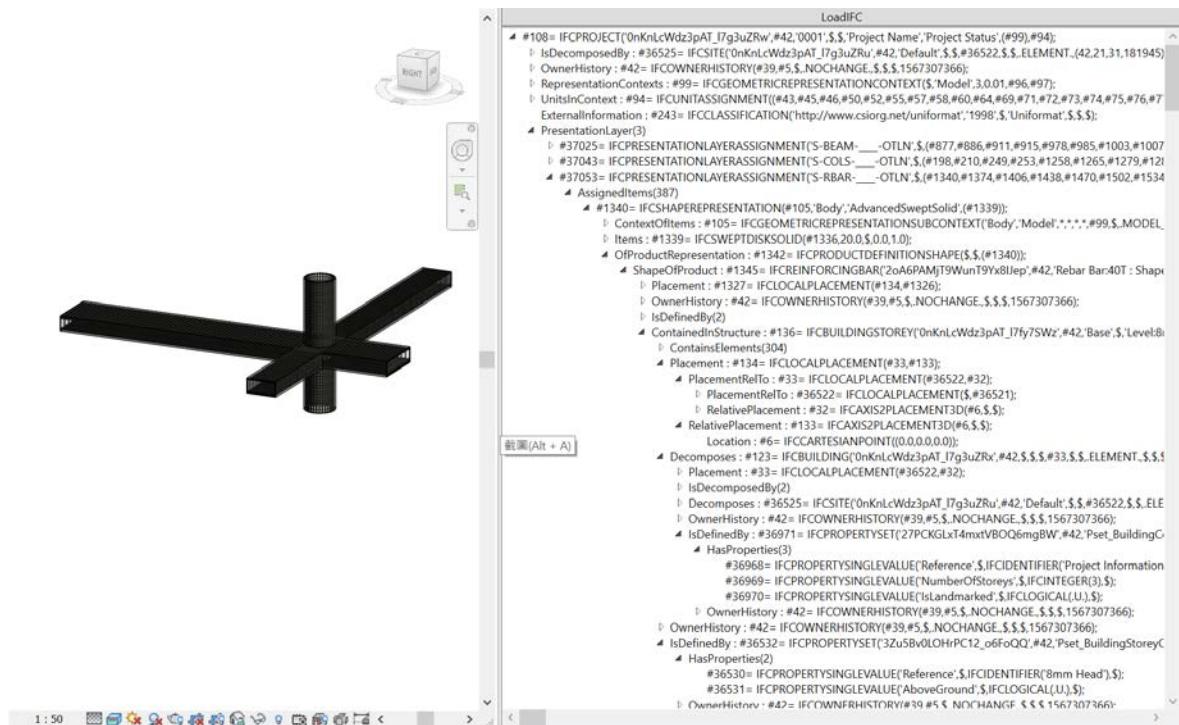


Figure 11. BIM model generated from clash-free solver

54	BF2D@HjP1@rL1@iL11@p1@13000@n1@e29.594@d40@g500@s280@G13000@w0@C84@
55	BF2D@HjP1@rL1@iL11@p1@13000@n1@e29.594@d40@g500@s280@G13000@w0@C84@
56	BF2D@HjP1@rL1@iL11@p1@13000@n1@e29.594@d40@g500@s280@G13000@w0@C84@
57	BF2D@HjP1@rL1@iL11@p1@13000@n1@e29.594@d40@g500@s280@G13000@w0@C84@
58	BF2D@HjP1@rL1@iL11@p1@13000@n1@e29.594@d40@g500@s280@G13000@w0@C84@
59	BF2D@HjP1@rL1@iL11@p1@13000@n1@e29.594@d40@g500@s280@G13000@w0@C84@
60	BF2D@HjP1@rL1@iL11@p1@13000@n1@e29.594@d40@g500@s280@G13000@w0@C84@
61	BF2D@HjP1@rL1@iL11@p2@14433@n1@e6.998@d16@g500@s32@Gr650@w360@w0@C81@
62	BF2D@HjP1@rL1@iL11@p2@14433@n1@e6.998@d16@g500@s32@Gr650@w360@w0@C81@
63	BF2D@HjP1@rL1@iL11@p2@14433@n1@e6.998@d16@g500@s32@Gr650@w360@w0@C81@
64	BF2D@HjP1@rL1@iL11@p2@14433@n1@e6.998@d16@g500@s32@Gr650@w360@w0@C81@
65	BF2D@HjP1@rL1@iL11@p3@14452@n1@e2.745@d10@g500@s20@Gr650@w360@w0@C81@

Figure 12. Part of output of Dynamo program

7. Conclusions and future work

In this study, openBIM standards are introduced along with some commonly used BIM specifications, and the parameters in BVBS specification are listed and parsed with the most updated IFC4Add2 schema in terms of semantic information of reinforcing elements. The data mapping between BVBS standard and IFC schema is made to address missing information in IFC, and in order to simplify the process of inputting reinforcement information into rebar cutting and bending machines, an IFC extension is proposed based on existing entities of reinforcing elements and incomplete conversion. With the aid of data mapping and IFC extension, the efficiency of reinforcing bar fabrication will be enhanced to a large degree and speed up the whole process to automation. However, some problems remain in the conversion in terms of Geometry Block in BVBS because different geometrical formulations are adopted for different shapes of reinforcing elements, which could be addressed and solved in the future along with more details of IFC extension. And for reinforcing elements other than bar and mesh, geometrical parameters of spiral links and lattice girders could be further modified instead of being determined just according to those of bar and mesh. The research plan also concerns the testing of the BVBS code generated from the developed Dynamo program in a local rebar factory to check the correctness of the code.

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VII. RISK AND SAFETY MANAGEMENT IN CONSTRUCTION II (C1)

Relationship between Stress Level and Reworks for Construction Professionals

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Abstract:

This paper presents a study investigating the relationship between stress level and reworks for construction professionals. As employees' work-life balance (WLB) becomes more important nowadays, controlling the level of stress in the workplace becomes more important as occupational stress has negative impacts on WLB. Reworks can be one severe occupational stressor as people suffer from stress when they need to redo their works. This study hypothesizes that there is a positive correlation between reworks and level of stress, meaning that people tend to show high level of stress when they need to redo their works. The hypothesis will be tested by checking the stress level when engineers redo their works because of changes or errors. An electroencephalography (EEG) sensor will be used to measure the stress level of engineers when they redo their works. For more accurate measure of stress, the stress level will also be measured by the galvanic skin response (GSR). This experiment is expected to prove that rework process is a severe stressor for construction professionals, which will contribute to lower productivity and poorer WLB. The finding will emphasize the importance of managing reworks in the construction industry, which will eventually help construction managers to control the level of employees' stress successfully.

Key words: Stress, Rework, EEG sensor, GSR sensor

1. INTRODUCTION

Occupational stress is one important factor to be managed for the successful delivery of construction projects. It is because occupational stress has negative impacts on individuals' performance in terms of productivity and safety [1]. Managing the occupational stress is particularly important for the construction industry as the industry is heavily labor-intensive [2, 3].

There have been various studies investigating the occupational stress. For example, by using a survey, Love et al. (2010) found that construction professionals working for a contracting organization on-site had higher levels of poor mental health and greater work stress than consultants [4]. Bell et al. (2012) argued that perceived job stress is associated with poorer work-life balance as occupational stress is related to adverse effects on employees' psychological and physical health [5]. Physical work requirements and psychological aspects of job demands can cause occupational stress, which affects well-being of employees and organization performance [6].

The negative correlation has been reported between the stress level and performance, meaning that high level of stress is associated with poorer performance. Based on a survey, Imtiaz and Ahmad (2009) found negative correlation between stress and job performance [7]. Halkos and Bousinakis (2010) also found that increased stress leads to reduced productivity [1].

There can be many different types of stressors. Leung et al. (2009) classified stressors into four categories: task stressors (e.g., work overload, role conflict, role ambiguity), organizational stressors (e.g., presence of bureaucracy, hierarchies, omnipotence of rules, unfair treatment), physical stressors

(e.g., work environment, home environment), and personal stressors [8]. For construction workers' job stress, Leung et al. (2016) presented five types of stressors, including safety equipment, supervisor support, co-worker support, job certainty, and job control [9].

Among the various stressors, this study focuses on rework. Rework is defined as "doing something at least one extra time due to non-conformance to requirements" [10]. Rework causes negative impacts on project performance. There have been many studies reporting that the costs of rework are substantial, ranging from 2.4% to 5% [11, 12].

This study investigates the relationship between stress level and reworks for construction professionals. Specifically, this study hypothesizes that there is a positive correlation between reworks and level of stress. When people need to redo their works, they tend to show high level of stress, which causes lower productivity and poorer work-life balance (WLB).

This paper consists of four sections. After the Introduction, the next section presents the literature review about stress, impact of stress in terms of productivity and WLB, and rework. The research hypothesis is provided based on the literature review in the same section. The third section, research methodology, presents how the stress level is measured. Electroencephalogram (EEG) and Galvanic Skin Response (GSR) sensors are introduced in this section. The data processing procedure including how filtering is conducted to remove noises from raw data and how the stress level is measured from the filtered data is presented as well. The last section briefly describes the experiment design and expected findings.

2. LITERATURE REVIEW

This section consists of four sub-section. The first sub-section presents the definitions of stress. The second sub-section provides the impact of stress on productivity and WLB. After the third sub-section describes rework, the last on presents the research hypothesis as well as research model.

2.1. Definition of Stress

Table 1 summarizes the definitions of stress. As shown in the table, stress has been defined in various ways. In general, most of the definitions describe stress as peoples' psychological, cognitive or behavioral reaction or response to any environmental, social or internal demand. Cannon (1929) suggested "fight or flight" concept to explain stress and its effects [20]. Also known as acute stress response, it is the concept that when the animal faces threats, it chooses to fight or run (flight) by activating sympathetic nervous system. The activation of a system stimulates the adrenal medulla, which secretes catecholamines such as epinephrine and norepinephrine. The secretion of these hormones induces increasing of heart rate and blood pressure, sweating and other physiological reactions. If these processes become chronic, it can lead to negative symptoms such as backache, headache, gastrointestinal problems. Anxiety, frustration, and burn-out are common psychological symptoms of excessive stress [21].

Table 1. Definitions of stress

Author	Stress Definition	Remarks
Lazarus (1993) [13]	<p>Three categories of stress</p> <ul style="list-style-type: none"> ● Harm: Psychological damage that has already been done ● Threat: The anticipation of harm that has not yet taken place but maybe imminent ● Challenge: Difficult demands people feel confident about overcoming by effectively mobilizing and deploying their coping resources 	
Selye (2016) [14]	Nonspecific response of the body to any demand	
Sharma and Gedeon (2012) [15]	Complex reaction patterns that often has psychological, cognitive and behavioral components	

Thoits (1995) [16]	Any environmental, social, or internal demand which requires the individual to readjust his/her usual behavior patterns	
The Health and Safety Commission (1999) [17]	Reaction that people have to excessive pressures or other demands placed on them	
Brough and Williams (2007) [18]	Harmful physical and emotional responses that occur when the requirements of the job do not match the capabilities, resources, or needs of the worker.	Workplace Stress
Australian Government Comcare (2008) [19]	A form of strain, a state of negative emotions, and arousal experienced in relation to the work role	Job Stress

2.2. Impact of Stress on Productivity and WLB

Chronic stress not only adversely affects health but also lowers personal working efficiency, which eventually affects the organizational performance. High level of stress in the workplace is perceived as a problem by management because it causes low productivity, high absenteeism, alcohol problems, drug abuse, and high blood pressure, which adversely affect organizational performance [7]. Tarafdar et al. (2007) stated that stress results in low productivity, dissatisfaction at work, lack of job involvement, and poor job performance [22]. High level of stress is also related to high level of dissatisfaction, which leads to employee turnover and this causes company costs in terms of recruitment, selection and training of new employees [1, 23].

High level of stress also leads to lower work-life balance (WLB). WLB is a way to tune life in the workplace and personal life. WLB is defined as the absence of conflict between work and family or personal roles [24, 25]. Hill et al. (2001) describes it as the degree to which an individual can simultaneously balance the emotional, behavioral and time demands of work, family and personal duties [26]. The absence of WLB causes poor performance and more absenteeism of employees [27]. It also has a significant relationship to other organizational outcomes such as turnover intention [28]. Regarding the relationship between stress and WLB, Bell et al. (2012) found that perceived job stress is associated with poorer WLB [5]. Ross and Vasantha (2014) argued that one signs of unhealthy WLB is work load increase which is one typical job stressor [29]. In addition, Chiang et al. (2010) showed that high WLB can decrease job stress [6].

2.3. Rework

Rework is defined as “doing something at least one extra time due to non-conformance to requirements” [10]. Another definition of rework is “the process by which an item is made to conform to the original requirement by completion or correction” [30]. There can be various causes of rework, including errors, omissions, failures, and damage [11, 31]. A change order can be another cause of rework [11, 31, 32].

Rework worsens construction project performance. Love and Li (2000) found that the costs of rework for residential and industrial buildings are 3.15% and 2.40% of contract value, respectively [11]. CII (2005) found that the direct costs caused by rework average 5% of total construction costs [12]. In addition to the project-level impact, rework also has negative impacts on individuals. Love (2002) reported that the architect and structural engineers’ morale is adversely affected when they need to constantly revise their documentation [31].

2.4. Research Hypothesis

This study investigates the relationship between stress level and reworks. Leung et al. (2010) classifies the task stressors into three categories [33]. Definitions of the three task stressors are summarized in Table 2. When reworks or change orders occur, people need to redo their works. Since they spend their time for the same scope of work, it is likely that they become overloaded. In addition, the decisions about reworks and change orders are not typically made by the employees who are responsible for redoing the works. Thus the level of autonomy should be low. In summary, it is reasonable to assume that reworks and change orders are related to work overload and lack of autonomy.

Based on the rationale, this study hypothesizes that there is a positive correlation between reworks and level of stress, meaning that people tend to show high level of stress when they need to redo their works.

Table 2. Definitions of Task Stressors

Task Stressor	Definition	Source
Work overload	the extent to which the job performance required in a job is excessive the job demands are too great for one individual	Iverson and Maguire (2000) [34] pg. 814 Leung et al. (2010) [33] pg. 1094
Role ambiguity	A lack of clarity about the expectations of the work role and about the scope and responsibilities of the job	Leung et al. (2010) [33] pg. 1094
Lack of autonomy	of the degree to which the job provides substantial freedom, independence, and discretion in scheduling the work and in determining the procedures to be used in carrying it out	Hackman and Oldham (1975) [35] pg. 162

Figure 1 shows the research model of this study. As mentioned previously, stress results in low productivity and WLB, which lead to worsen the organizational performance. In addition, as there are higher numbers of dual-earner couples and single parents, demand for workplace flexibility to take care of children and elders has increased substantially nowadays [36]. This kind of environmental shifts leads employees to desire more for WLB and employers began to offer more supports for their employees' WLB [37]. As a result, organizations should consider the level of employees' stress more carefully nowadays.

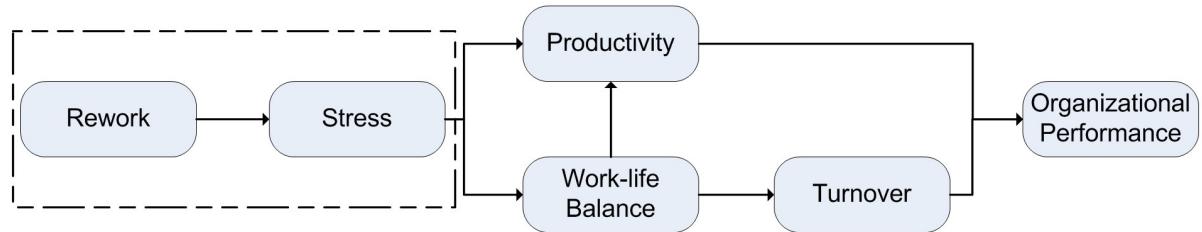


Figure 1. Research Model

For the research model shown in Figure 1, this study investigates the relationship between rework and stress which is shown in the dotted box in Figure 1.

3. RESEARCH METHODOLOGY

In order to study the relationship between rework and stress, this study uses two sensors measuring electroencephalogram (EEG) and galvanic skin response (GSR). This section introduces them and presents how stress can be measured by them quantitatively.

3.1. Electroencephalogram (EEG)

EEG is an electrical signal generated by the activation of neurons in the brain. It can be measured by attaching electrodes along the scalp. As EEG is a non-invasive measure technique of the brain's activation, it is widely used across neuroscience and medical fields [2,15,38]. EEG signals can be classified by frequency, such as delta (0.5-4 Hz), theta (4- 8Hz), alpha (8-13 Hz), beta (13-30 Hz) and gamma (> 30 Hz) [39,40]. Each frequency region represents specific states. For example, delta frequency range is occurred during deep sleep [41]. In this study, beta frequency will be used to measure

the level of stress. There have been many studies using beta frequency to measure the level of stress as there is a positive correlation between beta frequency range and the level of stress [41,42,43,44,45].

The wireless EEG measure device EPOC+ by EMOTIV shown in Figure 2(a) is used to measure the EEG signals. The device provides 14 electrodes as shown in Figure 2(b). Jebelli et al. (2018) and Hwang et al. (2018) well describe the process to measure stress from the raw data generated from the device [39,40]. After the raw data are extracted from the EEG measure device, they need to be processed to remove extrinsic and intrinsic artifacts. Extrinsic artifacts are the noises which are not generated by physiological reasons. Examples of extrinsic artifacts are electrode popping or mechanical noises. Intrinsic artifacts are the noises generated by body changes. Eye blinking, eye movement, and facial muscle movement are examples of intrinsic artifacts. Such noises can be filtered via EEG signal processing tools [40]. In this research, EEGLab will be used to process the EEG signals. EEGLab is an open-source software made by Swartz Center for Computational Neuroscience(SCCN) of the University of California San Diego. It was made for EEG data analysis tools for MATLAB. EEGLab has been widely used for research and recognized as the software most widely used for electrophysiological data analyses [46]. As the frequencies of extrinsic artifacts are different from EEG signals, it is necessary to filter the higher or lower than the frequencies of EEG signals. As this study focuses on the measurement of beta frequency which ranges 13 to 30 Hz, the high and low frequency cutoff in this study were determined as 30Hz and 0.5Hz, respectively. The intrinsic artifacts have similar frequencies to EEG signals. Independent component analysis (ICA) will be applied to remove the intrinsic artifacts. ICA is a method for signal processing and data analysis and have been widely used to remove intrinsic artifacts in EEG signals [47,48,49]. In this method, it is assumed that the recorded EEG signal can be analyzed as the sum of independent components, and also can be decomposed as independent components. After decomposing EEG signal in to independent components, unwanted noises such as eye-blinking or muscle movement can be removed. After the extrinsic and intrinsic artifacts are removed, the beta frequency will be presented in the time domain form. While the beta frequency can be measured by various locations in Figure 2(b), this study specifically uses the frequency values at FC5 and FC6 as the beta frequency values measured at these locations have been used to represent the level of stress [50,51]

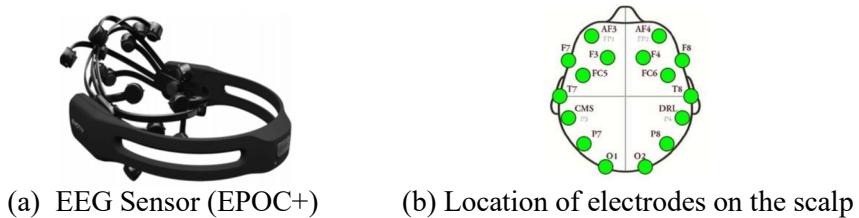


Figure 2. EEG Sensor and Location of Electrodes

3.2. Galvanic Skin Response (GSR)

GSR is the method of measuring change of skin conductance at surface [52]. As mentioned previously, in a stressful situation, sympathetic nervous system is activated. Activation of sympathetic nervous system leads to sweating, which changes the skin conductance. Therefore, in a controlled situation, increasing GSR means increasing stress [53]. As GSR is only affected by sympathetic nervous system, there is few intervening variables between stress and GSR. Thus GSR can be a good indicator to measure stress [52].

Empatica E4 wristband will be used to measure the GSR signal. It has been widely used to measure GSR [54,55,56,57]. As it is a wristband as shown in Figure 3(a), subjects feel more comfortable to use this equipment than other types of equipment installed on their fingers as shown in Figure 3(b).

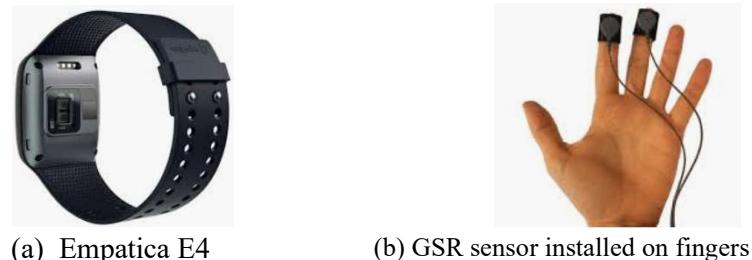


Figure 3. GSR Sensors

Recorded GSR signals will be processed by Ledalab. Ledalab is open source software for analyzing the skin conductance data in MATLAB. It helps users to filter their skin conductance data, and decompose for analyses [58,59,60,61]. Similar to the EEG sensor, GSR signals will be presented in the time domain.

4. EXPERIMENT DESIGN and PRELIMINARY FINDINGS

This study will investigate the relationship between stress level and reworks as shown in Figure 1. A preliminary test was conducted. A subject was asked to draw 3 simple drawings for a minute each and told to redraw them. He was told to stay calm for 20 seconds at the beginning of experiment, and the rework order was given at 200 seconds. Figure 4 shows the beta frequency from the preliminary test. They were obtained in FC5 and FC6 where the beta frequency can be measured. As shown in the figure, the beta frequency fluctuated substantially when they were asked to redo the work, indicating that the subject felt stress.

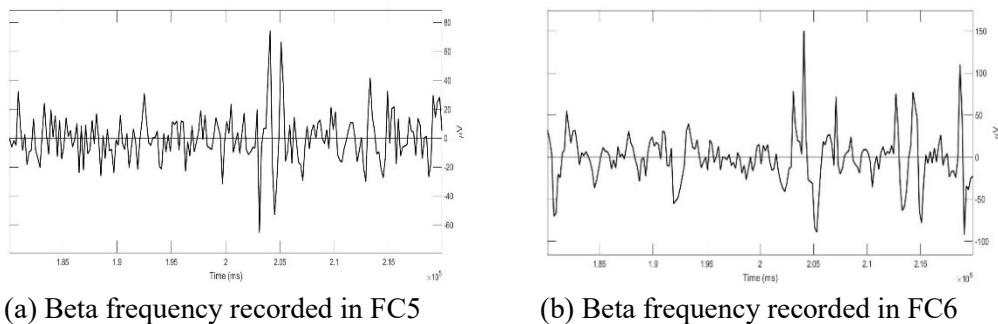


Figure 4. Preliminary EEG data

Figure 4 show that beta frequency of FC5 and FC6 was increased when rework order was given. Likewise figure 6 show that GSR value increase right after the rework order. Figure 5 represent the mean PSD value at certain situation such as stable, normal and stressed. Stable is the period when subject stay calm at the beginning of experiment and normal situation is the period when subject draw the plan. Stressed means the period when rework order was given. As can be seen at figure 5, mean PSD value of FC5 increased sequentially from stable to stressed situation. Contrary, mean PSD value for FC6 behave different. Mean PSD value of FC6 at stable situation is bigger than Normal one. But as mean PSD value at stressed is bigger than the others, it's possible to say that stress is detected. As bigger mean PSD value means more stress, we can say that current experiment set up can detect the stress from rework.

Figure 5 compares the mean power spectral density (PSD) values at different conditions such as stable, normal and stressed. The stable condition is the period when a subject stays calm at the beginning of experiment. The normal condition is the period when a subject works on the drawings. The stressed condition means the period when rework order was given. As can be seen in figure 5, the mean PSD values at FC5 and FC6 show were the highest in the stressed condition. As the bigger mean PSD value means higher level of stress, it can be concluded that rework causes stress.

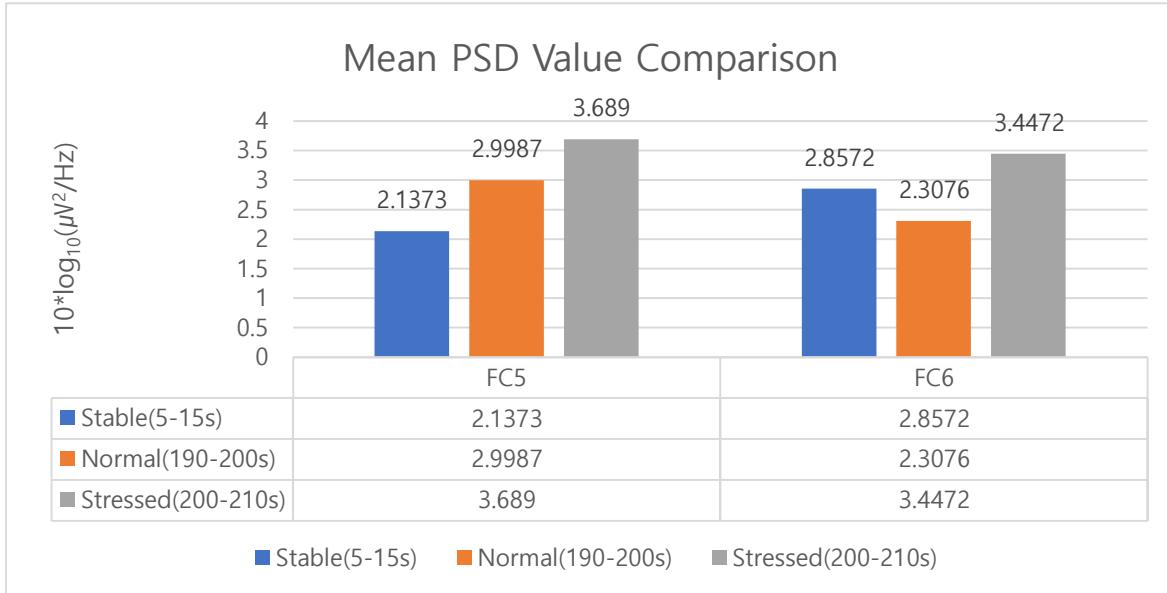


Figure 5. Mean PSD Value

Figure 6 shows the preliminary GSR data. As shown in the figure, when rework was assigned, the level of skin conductance increased significantly. As increasing GSR means increasing stress, the result also shows that the subject felt stress when rework order was given.

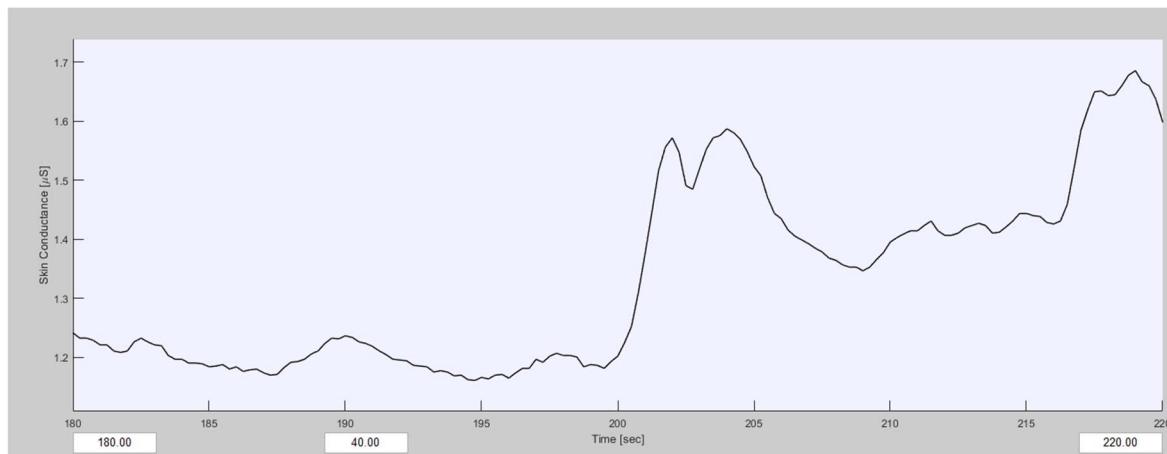


Figure 6. Preliminary GSR data

As presented in the previous section, there have been many studies asserting that high level of stress reduces productivity [7,22]. Thus if the hypothesis is validated, it can be argued that reworks contribute to lowering productivity. This can be an interesting finding especially to practitioners. There has been a practice that companies award a contract at bids below a reasonable price and then

try to recover their compensation by making change orders. Some researchers described this as change order abuse [62,63,64]. As a change order can be another cause of rework, employees feel stressed when they are directed to work change orders. In addition, this kind of practice will lower the employees' WLB, which will lead to turnover as people pay more attention on WLB. Thus it is possible that companies' short-term profits will increase with the practice but their long-term profits may decrease. Future studies will try to validate these statements by testing the relationships in Figure 1.

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Construction Equipment Accidents by Time

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Abstract: This paper investigates the construction equipment accidents by time. Construction sites are unique with many different hazardous conditions which cause accidents. According to the Occupational Safety and Health Administration (OSHA), accidents related to construction equipment are one of the most leading causes of fatal injuries in the construction industry. While there have been many studies investigating the equipment-related accidents, few research studies provided in-depth analyses about the time that accidents frequently occurred. By using the OSHA accidents data collected between 1997 and 2012, this paper analyzed the accidents data by time, equipment type including excavator, backhoe, dozer, and crane, accident cause, and injury class. The analyses revealed that the time window with most accidents was between 13:00 and 13:59. In terms of the injury class, the time windows with the highest numbers of equipment accidents were between 13:00 and 13:59 and between 11:00 and 11:59 for fatality and hospitalization, respectively. For the accident causes, equipment operator's error was the highest number of accident causes. It is expected that findings from the analyses can be used to more strategically develop management plans and guidelines to prevent accidents related to construction equipment to practitioners.

Key words: construction equipment accident, safety, equipment, accident time, accident frequency

1. INTRODUCTION

The construction industry has been regarded as one of the most hazardous industries [1]. MacCollum [2] pointed out that the US construction industry accounts for approximately 7% of the total workforce, but construction worker deaths account for about 20% of all industrial fatalities. For over two decades, numerous studies have been conducted to reduce accidents in the construction industry [3-6]. Unfortunately, considering the fact that 1,008 out of 4,779 fatalities occurred in the construction industry in 2018 [7], the statistics remain very similar nowadays.

Among the various causes of work-related injuries and fatalities in the construction industry, those related to construction equipment have been one leading cause in the U.S. [8]. One-quarter of the fatal accidents in construction industry are the result of collisions, rollovers, stuck-by accidents, and other equipment-related accidents [1]. In 2014, the Bureau of Labor Statistics reported that the construction industry experienced 902 fatalities of which 15.2% (137 fatalities) resulted from workers coming into contact with objects or construction equipment [9]. Among the 92 construction equipment fatalities, 27 cases were related to excavating machinery such as backhoe, bulldozer, and excavator and 14 cases were related to cranes [10].

Regarding the accidents related to construction equipment, while there have been many studies investigating the technologies preventing accidents [11-14] and causes of accidents [15-18], few studies

have investigated when, how frequently, and how severely accidents related to construction equipment have occurred.

This study investigates the accidents related to construction equipment by time. From 20,997 accidents recorded between 1997 and 2012 in the Occupational Safety and Health Administration (OSHA) Integrated Management Information System (IMIS) database, this study extracted data containing equipment type and time that the accident occurred. From those data, this study identified the time that accidents occurred for four types of equipment including backhoe, crane, dozer, and excavator. In addition, this study presents the accidents by time and major injury class and by time and accident causes categorized by the authors from the description of each accident in the dataset. The findings of this study contribute to helping practitioners establish more sophisticated plans to prevent construction equipment accidents, which can eventually contribute to reducing such accidents.

2. Literature Review

The section consists of two sub-sections. The first sub-section presents the studies about equipment accidents. The second sub-section summarizes the studies about accidents by time.

2.1. Studies about equipment accidents

Table 1 summarizes the studies investigating safety in construction equipment. As shown in the table, we classified the studies into two categories: preventing technology and accident cause analysis.

There have been many studies proposing technologies to prevent accidents related to construction equipment. For example, Teizer et al. [11] used radio frequency remote sensing and actuating technology to prevent accidents by providing warnings to equipment operators in real time. Golovina et al. [12] presented a method for recording, identifying, and analyzing interactive hazardous near miss situations between workers-on-foot and heavy construction equipment by using spatiotemporal global position system (GPS) data. Zhu et al. [13] proposed filters for predicting workers' movements and mobile equipment to prevent collisions between them.

Another topic being studied about equipment accidents was related to causes of accidents. Beavers et al. [15] studied proximal causes of crane-related fatalities by using the OSHA accident data recorded between 1997 and 2003. Hinze et al. [16] investigated the causes of "stuck-by" accidents and identified the frequencies of each cause categorized in terms of age, material involved, human errors, and environmental factors. Kazan and Usmen [18] used OSHA's earthmoving equipment accident data and investigated the frequencies of accidents in terms of fatal and nonfatal by environmental factors and human factors.

2.2. Studies about accidents by time

There are several research studies including information about the time that certain types of accidents occurred [19-23]. Kines [19] studied the construction workers' falls through roofs. In the study, he found that the time window between 13:00 and 15:59 has the highest number of fatal accidents and that between 10:00 and 12:59 has most serious accidents in the construction industry in Denmark. Huang and Hinze [4] conducted a research study about fall accidents and found that the time window with the least accidents was between noon and 13:00 and that with the most accidents was between 10:00 and 11:00 in the morning and between 13:00 and 14:00 in the afternoon. When investigating the causes of 40 fatal accidents occurred in Singapore construction sites, Ling et al. [20] found that many fatal accidents occurred around tea breaks which are around 10 am, 3 pm, and 12:30 pm. For the safety management of highway construction projects, Kim et al. [21] found that accident occurrence time varies depending on the types of works such as drainage, tunnel, and structure. Because of this time difference, they recommended that safety precautions and management should vary by work type and time. Wong et al. [22] investigated major causes of fatal accidents using falls from height (FFH) data in Hong Kong. The authors found that fatal accidents occurred more frequently between 10:00 and 11:00, 13:00 and 15:00, and 17:00 and 18:00. As the first two time periods are when workers start their works in the morning and afternoon, respectively and the last time period is when workers wrap up their

works, the authors asserted that careful inspection should be done when workers start and finish their works. Chiang et al. [23] studied fatal construction accidents in Hong Kong. They found that most fatal accidents occurred in late morning and early afternoon.

We conducted a literature review about equipment accidents and accident time. While there have been many studies for these topics, there has been no study investigating the equipment accidents by time. The current body of knowledge lacks when accidents related to construction equipment occurred, how frequently they occurred, and how severe they are. With the information, practitioners will be able to establish more effective plans to reduce the accidents related to construction equipment.

Table 1. Research studies about equipment accidents

Topic Category	Paper	Contents
Technologies preventing accidents	Teizer et al. [11]	This research presented real-time pro-active RF warning sensing and actuating technology that is able to enhance construction equipment safety.
	Golovina et al. [12]	The study showed method of identifying dangerous near miss situations between workers-on-foot and heavy construction equipment.
	Zhu et al. [13]	This study introduced Kalman filters for predicting the movements of the workers and mobile equipment on construction sites.
	Pradhananga and Teizer [14]	This research presents technology and algorithms that is able to identify equipment activity using GPS data.
Accident Causes	Beavaers et al. [15]	Using crane-related fatal events, this study investigated proximal and distal causes of fatalities which are organized as “stuck by load”, “electrocution”, “crushed during assembly/disassembly”, “failure of boom/cable”, “crane tip over”, “stuck by counter weight”, and “falls”
	Hinze et al. [16]	This paper presented the accident analyses focusing on stuck-by accident through comprehensively analyzing the accidents involved factors and frequency of cases.
	Hinze and Teizer [1]	This paper studied visibility-related fatalities by analyzing OSHA data and examined the root causes of visibility-related fatal accidents.
	Hinze et al. [17]	This study identified the major causes of earthmoving equipment fatalities and studied the relationship between the nature of an accident and moving direction of equipment as well as the role of the victim and direction of moving of equipment.
	Kazan and Usmen [18]	This paper presented variables and their effects on the injury severity for earthmoving equipment. The causal factors in this study were categorized as human factors and environmental factors.

3. Methodology

To investigate when accidents related to construction equipment occur, this study used the OSHA IMIS database. After obtaining the raw data from OSHA, it was necessary to sort out the accident data related to construction equipment. This was done by using some keywords such as backhoe, excavator, crane, trackhoe, and bulldozer. Considering the degree of frequent use in construction sites and the degree of involvement in accidents, this study focuses on four types of equipment: backhoe, crane, dozer, and excavator. Backhoe and dozer are the equipment highly used and frequently involved in accidents [24]. Dozers are included because accidents involved in the equipment showed high level of fatality [8]. Cranes are included as the number of crane accidents is always high [24].

For the accident data related to construction equipment, this study extracted four parameters including accident occurrence time, equipment type, injury class, and accident cause. For each accident, the raw dataset already contained the injury class information such as fatality, hospitalization, and non-hospitalization. The accident occurrence time and accident cause were extracted from the case

summary. Figure 1 shows an example. The OSHA IMIS data provide a brief case summary for each accident. From the summary, we captured the time information. For the accidents that relate to the aforementioned four types of equipment, 415 accidents data contain time information.

Case Summaries	Cause	Time	Original Class
At 9:00 a.m. on January 12, 1999, Employee #1 was the operator of an <u>excavator</u> or digger which made an excavation approximately 5 foot deep and 20 foot long. The excavator made <u>contact with an electrical line of 7,000 volts</u> . While trying to get off the machine, Employee #1 stepped onto the ground which resulted in his being electrocuted.	1	9	FATALITY

Figure 1. Data Coding: An Example

In addition to the time information, the cause of accidents was extracted by reviewing the case summaries. We developed seven categories shown in Table 2. Different research team members coded the accident causes individually. Then, each coded cause was cross-checked by the members collectively. If the cause of one accident was coded differently by the research team members, the team reviewed it together and made the final decision.

Table 2. Accident causes coded from the case summaries in the dataset

Number	Accident Cause
1	Equipment operator's error
2	Accident caused by co-workers
3	Accident caused by site condition such as ground collapse and weather
4	Lack of communication
5	Mechanical defect
6	Lack of prior investigation
7	Inadequate rules and systems

For the data, this study presents the descriptive statistics. In order to discuss the results, several variables used in this study were organized by cross-tabulation. Accidents by time and equipment, by time and injury class, and by time and accident causes are presented in the following section.

4. Results

This section consists of three sub-sections. The first sub-section presents the accident by time and equipment. The second sub-section deals with the accident by time and injury class. The third sub-section discusses the accident by time and accident cause.

4.1. Accidents by time and equipment

Table 3 shows the number of accident by time and equipment type. The table also presents the percentage values calculated as the ratio of the number of accidents occurred in a specific time window and the total number of accidents for each type of equipment. Each time window was set at one hour interval. Considering the time that labors usually work, two time windows from 0:00 to 6:59 and from 19:00 to 23:59 include longer time periods than other windows. There can be some interesting findings from the table. First, the time window with the most accidents was between 13:00 and 13:59, followed by 11:00 and 11:59. More than 25% of equipment-related accidents occurred at these time windows. This finding is consistent with a previous study discussing that accidents occur frequently before and after lunch break in construction sites [23]. Second, for the type of equipment, the crane has the highest

number of accidents. It should not be concluded that the crane is the most dangerous equipment. This is because this study did not take the work hours into account. The crane is one of the most widely used equipment on construction sites [25]. Cranes are very expensive yet commonly operated machinery on sites. Thus, it is reasonable to assume that the overall work hour of cranes is higher than the work hours of other types of equipment. If comparing the number of accidents per one workhour, it is possible that other types of equipment have higher values than cranes. When comparing the number of accidents for each time window and types of equipment together, the crane, dozer, and excavator have the highest numbers of accidents between 11:00 and 11:59. The excavator has the same number of accidents between 10:00 and 10:59 as well. For the backhoe, time window between 11:00 and 11:59 shows the highest number of accidents.

Table 3. Accidents by Time and Equipment Type

Time	Equipment				Total
	Backhoe	Crane	Dozer	Excavator	
0:00 ~ 6:59	3 (3.1%)	3 (1.5%)	1 (2.4%)	0 (0.0%)	7 (1.7%)
7:00 ~ 7:59	6 (6.3%)	10 (5.1%)	2 (4.9%)	4 (4.9%)	22 (5.3%)
8:00 ~ 8:59	6 (6.3%)	16 (8.1%)	3 (7.3%)	7 (8.6%)	32 (7.7%)
9:00 ~ 9:59	4 (4.2%)	21 (10.7%)	6 (14.6%)	11 (13.6%)	42 (10.1%)
10:00 ~ 10:59	12 (12.5%)	20 (10.2%)	2 (4.9%)	13 (16.1%)	47 (11.3%)
11:00 ~ 11:59	13 (13.5%)	25 (12.7%)	6 (14.6%)	5 (6.2%)	49 (11.8%)
12:00 ~ 12:59	8 (8.3%)	14 (7.1%)	3 (7.3%)	7 (8.6%)	32 (7.7%)
13:00 ~ 13:59	11 (11.5%)	30 (15.2%)	8 (19.5%)	13 (16.1%)	62 (14.9%)
14:00 ~ 14:59	9 (9.4%)	21 (10.7%)	3 (7.3%)	7 (8.6%)	40 (9.6%)
15:00 ~ 15:59	11 (11.5%)	10 (5.1%)	1 (2.4%)	6 (7.4%)	28 (6.8%)
16:00 ~ 16:59	5 (5.2%)	9 (4.6%)	2 (4.9%)	2 (2.5%)	18 (4.3%)
17:00 ~ 17:59	3 (3.1%)	4 (2.0%)	1 (2.4%)	3 (3.7%)	11 (2.7%)
18:00 ~ 18:59	2 (2.1%)	4 (2.0%)	2 (4.9%)	2 (2.5%)	10 (2.4%)
19:00 ~ 23:59	3 (3.1%)	10 (5.1%)	1 (2.4%)	1 (1.2%)	15 (3.6%)
Total	96 (100%)	197 (100%)	41 (100%)	81 (100%)	415 (100%)

4.2. Accidents by Time and Injury Class

Table 4 summarizes the numbers of accidents by time and injury class. First of all, when comparing the total numbers of accidents by injury class, 230 cases out of 415 were fatalities and only 28 cases were non-hospitalization. This indicates that accidents involved in construction equipment are substantially severe. The time windows with the highest number of accidents were different by injury class. Those time windows are 13:00 to 13:59, 11:00 to 11:59, and 9:00 to 9:59 for fatality, hospitalization, and non-hospitalization, respectively.

As the time windows with the highest number of accidents vary by injury class, it was thought that the trend of the number of accidents over time may differ by injury class. Figure 2 illustrates the numbers of accidents over time by injury class. As shown in the figure, both the numbers of fatality and hospitalization tend to increase until noon. After the time window between noon and 12:59 which is usually lunch time so the work hours should be reduced, the numbers of accidents increase dramatically between 13:00 and 13:59. Non-hospitalization, on the other hand, has the highest number of accidents between 9:00 and 9:59 and the numbers tend to decrease. One presumable reason why the trends of the numbers of accidents are different by injury class is that the causes of accidents are different.

Table 4. Accidents by Time and Injury Class

Time	Injury Class			Total
	Fatality	Hospitalization	Non-Hospitalization	
0:00 ~ 6:59	3 (1.3%)	3 (1.9%)	1 (3.6%)	7 (1.7%)
7:00 ~ 7:59	10 (4.4%)	8 (5.1%)	4 (14.3%)	22 (5.3%)
8:00 ~ 8:59	17 (7.4%)	13 (8.3%)	2 (7.1%)	32 (7.7%)
9:00 ~ 9:59	22 (9.6%)	13 (8.3%)	7 (25.0%)	42 (10.1%)
10:00 ~ 10:59	26 (11.3%)	18 (11.5%)	3 (10.7%)	47 (11.3%)
11:00 ~ 11:59	23 (10.0%)	25 (15.9%)	1 (3.6%)	49 (11.8%)
12:00 ~ 12:59	20 (8.7%)	10 (6.4%)	2 (7.1%)	32 (7.7%)
13:00 ~ 13:59	38 (16.5%)	22 (14.0%)	2 (7.1%)	62 (14.9%)
14:00 ~ 14:59	23 (10.0%)	17 (10.8%)	0 (0.00%)	40 (9.6%)
15:00 ~ 15:59	13 (5.7%)	12 (7.6%)	3 (10.7%)	28 (6.7%)
16:00 ~ 16:59	12 (5.2%)	5 (3.2%)	1 (3.6%)	18 (4.3%)
17:00 ~ 17:59	9 (3.9%)	2 (1.3%)	0 (0.0%)	11 (2.7%)
18:00 ~ 18:59	7 (3.0%)	3 (1.9%)	0 (0.0%)	10 (2.4%)
19:00 ~ 23:59	7 (3.0%)	6 (3.8%)	2 (7.1%)	15 (3.6%)
Total	230 (100%)	157 (100%)	28 (100%)	415 (100%)

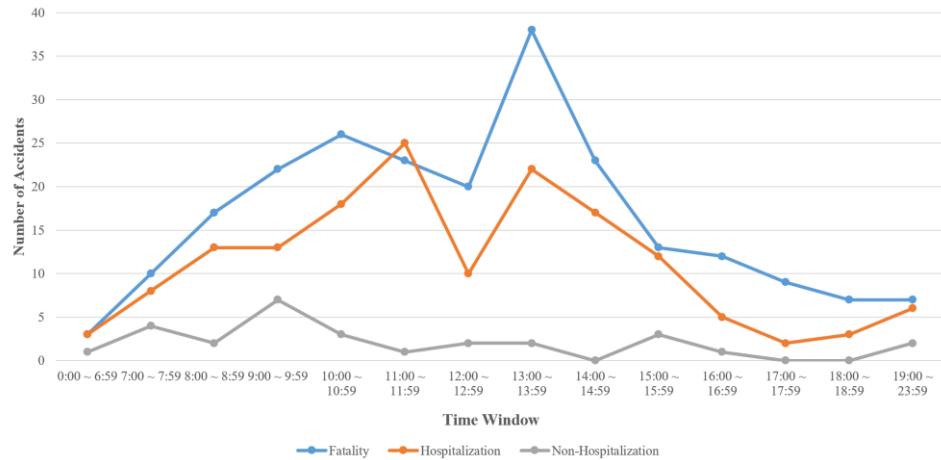


Figure 2. Accidents by Time and Injury Class

4.3. Accidents by Time and Accident Cause

Table 5 presents the accidents by time and accident cause. As not all data contain information about the accident causes, the total number of data in Table 5 is 220. As shown in the table, 90 accidents were involved in the equipment operator's error. It represents 41% of the total number of accidents. The

accident cause with the second most accidents is the accidents caused by co-workers. As 44 accidents are categorized as this cause, 134 accidents or 61% of accidents were related to human errors. The number of accidents related to mechanical defect is 38. The number of accidents caused by site condition such as ground collapse and weather is 29. From these values, it can be concluded that construction equipment accidents are more caused by errors of the workers such as operators and co-workers.

Table 5. Accidents by Time and Accident Cause

Time	Accident Cause						
	1	2	3	4	5	6	7
0:00 ~ 6:59	1 (1.1%)	1 (2.3%)	0 (0.0%)	0 (0.0%)	1 (2.6%)	0 (0.0%)	0 (0.0%)
7:00 ~ 7:59	7 (7.8%)	4 (9.1%)	1 (3.4%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
8:00 ~ 8:59	9 (10.0%)	4 (9.1%)	2 (6.9%)	1 (20.0%)	0 (0.0%)	0 (0.0%)	1 (12.5%)
9:00 ~ 9:59	11 (12.2%)	8 (18.2%)	3 (10.3%)	0 (0.0%)	5 (13.2%)	1 (16.7%)	1 (12.5%)
10:00 ~ 10:59	11 (12.2%)	5 (11.4%)	3 (10.3%)	0 (0.0%)	4 (10.5%)	1 (16.7%)	1 (12.5%)
11:00 ~ 11:59	12 (13.3%)	6 (13.6%)	2 (6.9%)	1 (20.0%)	6 (15.8%)	1 (16.7%)	1 (12.5%)
12:00 ~ 12:59	7 (7.8%)	2 (4.5%)	4 (13.8%)	1 (20.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
13:00 ~ 13:59	11 (12.2%)	1 (2.3%)	8 (27.6%)	1 (20.0%)	9 (23.7%)	2 (33.3%)	1 (12.5%)
14:00 ~ 14:59	6 (6.7%)	4 (9.1%)	2 (6.9%)	0 (0.0%)	7 (18.4%)	0 (0.0%)	1 (12.5%)
15:00 ~ 15:59	6 (6.7%)	1 (2.3%)	2 (6.9%)	0 (0.0%)	1 (2.6%)	0 (0.0%)	2 (25.0%)
16:00 ~ 16:59	4 (4.4%)	3 (9.1%)	1 (3.4%)	0 (0.0%)	1 (2.6%)	0 (0.0%)	0 (0.0%)
17:00 ~ 17:59	1 (1.1%)	1 (2.3%)	0 (0.0%)	1 (20.0%)	3 (7.9%)	0 (0.0%)	0 (0.0%)
18:00 ~ 18:59	2 (2.2%)	3 (6.8%)	1 (3.4%)	0 (0.0%)	1 (2.6%)	0 (0.0%)	0 (0.0%)
19:00 ~ 23:59	2 (2.2%)	1 (2.3%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	1 (16.7%)	0 (0.0%)
Total	90 (100%)	44 (100%)	29 (100%)	5 (100%)	38 (100%)	6 (100%)	8 (100%)

When interpreting the trend shown in Figure 2, it was thought that one possible reason why the time windows with most accidents were different by injury class is different accident causes. Figure 3 illustrates the accidents by time and accident cause. Note that we removed the causes with less than 10 accidents in the figure. There can be two interesting findings from the figure. First, trend over time for the non-hospitalization accidents in Figure 2 is similar to that for the accidents caused by co-workers in Figure 3. The number of accidents for both is the highest between 9:00 and 9:59 and tends to decrease with time. This study cannot validate the causal relationship between the two. But, it may be interesting to further investigate the relationship in future studies. Second, the time windows with the most accidents are between 11:00 and 11:59 and between 13:00 and 13:59. One can conjecture that reduced concentration due to continued work and drowsiness after lunch can be the reasons why those time windows have high numbers of accidents. As those reasons are related to human errors, the number of accident causes related to human errors such as operators' error and accidents caused by co-workers should be high at those time windows. As shown in Figure 3, equipment operator's error shows high number of accidents at those time windows. However, there is only one accident caused by co-workers between 13:00 and 13:59. Surprisingly, accidents related to site condition and mechanical defect show high numbers of accidents between 13:00 and 13:59. As those causes are not human errors, there is no reason for those causes to have high numbers of accidents at the time window. Future studies further investigating the causes of accidents involved in construction equipment are recommended.

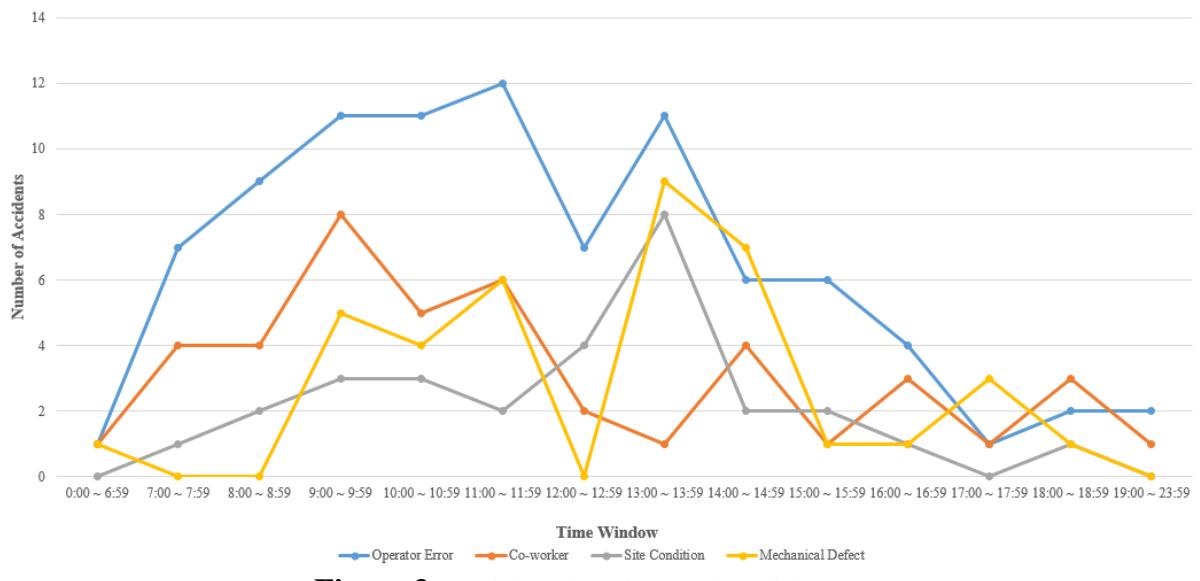


Figure 3. Accidents by Time and Accident Cause

5. Discussion and Conclusion

This study investigated the construction equipment accidents by time. By using the OSHA IMIS accident data, this study analyzed the accidents by time, by time and injury class, and by time and accident cause. From the analyses, this study found that construction equipment accidents were most frequent before and after lunch break, between 11:00 and 11:59 and 13:00 and 13:59. Reduced concentration due to continued work or urge to finish works before lunch break can be presumable reasons for the high number of accidents before lunch break. Drowsiness after lunch can be one possible reason for the high number of accidents after lunch break. As more than 50% of construction equipment accidents are fatality as shown in Table 4, it is very important to reduce these accidents. For this, future research studies about the accidents occurred in these time windows are recommended. This study also found that the time windows with highest number of accidents were different by injury class. The time window with the most fatality accidents is between 13:00 and 13:59. For the accident causes, this study found that more than 60% of construction equipment accidents were caused by human errors such as operator's error and accidents related to co-workers. Thus, research on how to reduce human errors of equipment operators is required for future studies.

The major contribution of this study is to provide information about construction equipment accidents. Understanding when construction equipment accidents occurs, how severe they are, and why they occur should help practitioners establish safety management plans and safety training programs. This leads to reduce the construction equipment accidents that more than 50% of victims die. Specifically, practitioners should focus on reducing human errors after lunch break as those are the cause and time window with most fatalities. One major limitation of this study is the lack of work hours for each time window. With the information, one can study the number of accidents per work hour and this measure should more precisely represent more dangerous time windows. Another limitation is that this study simply presents the numbers of accidents by various dimensions. Future studies conducting statistical analyses with the dataset are recommended.

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Construction Safety Training Methods and their Evaluation Approaches: A Systematic Literature Review

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Abstract: Due to hazardous working environments at complex, unstructured, and dynamic construction sites, workers frequently face potential safety and health risks throughout the construction process. In this regard, addressing safety challenges remains one of the top priorities. Construction workers' ability to identify and assess risks is acquired through training, which is one of the primary key factors to determine their safety and wellbeing in hazardous working environments. As such, safety managers constantly focus on the effectiveness of the training materials provided to the workers. However, the construction workers are considerably at greater risk of injuries and fatalities compared to the workers in other industries. In this regard, further studies are required to build up a body of knowledge on the conventional safety training approaches as well as their evaluation techniques in order to boost up the adoption by the practitioners in a widespread manner. This paper provides a systematic review of the current safety training approaches and the various techniques for measuring their effectiveness. The attributes of the current safety training methods for construction workers and their evaluation techniques are identified and analyzed. Results indicated that: 1) immersive environment-based training methods are effective than the traditional safety training methods; 2) this effectiveness can be empirically supported by evaluation strategies, but the current techniques are subjective, intrusive, and error-prone. This research offers fresh opportunities to investigate the training strategies by objectively monitoring the physiological responses of construction crews. The results of this study can be used by researchers and practitioners to identify and determine optimal safety training programs that could potentially become ubiquitous in the construction industry.

Keywords: construction, safety, training, evaluation, review

1. INTRODUCTION

The construction industry is one of the most labor-intensive industries, offering a large number of employment opportunities for millions of people worldwide [1]. Statistics show that construction workers are considered at greater risk of injuries and fatalities than the workers in other industries [2]. According to the US Bureau of Labor Statistics (BLS) [3], 1,008 workers lost their lives while working on construction sites in the US in 2018. Even though the construction sector constitutes about 5% of the workforce in the US, fatal injuries in the construction account for about 20.7% of occupational deaths across all industries [4]. As such, the construction workplace, with the complicated construction process,

rapidly changing working locations, and dynamic resources, including staff, equipment, and materials, is regarded as one of the most unsafe industries. As a result, addressing safety challenges remains one of the top priorities in the construction industry.

Previous research suggests that most of the injuries occurring in construction worksites can be attributed to the inability of the workforce to predict, identify, and respond to hazards at the workplace [5]. More than 70% of construction injuries are associated with poor safety knowledge [6]. When workers underestimate the potential safety risk, they are more likely to indulge in risk-taking behavior [5]. As such, the ability to identify potentially hazardous conditions is an indispensable tool to mitigate risk, indulge in safe behavior, and achieve optimal construction environment. However, current studies show that workers, on average, are not able to identify more than 50% of safety hazards in a typical construction workplace [7]. Construction workers' ability to identify risks and their subjective analysis of the magnitude of those risks determine their attitude towards the potentially risky situation and their safety. To this end, safety training is an essential tool that raises workers' awareness of common risks associated with construction jobsite by augmenting the risk perception knowledge of the workforce. Also, the training encourages workers to make safety-conscious decisions, minimize risk, and avoid potential injuries. The variety of training schemes guarantees the attainment of a risk-sensitive attitude and ensures a safety climate in the workplace. In particular, the off-site instructional and on-site hands-on training programs allows for the systematic and methodological comprehension of safe behavior and proper practice in a construction jobsite. Researchers have highlighted that insufficient training is a significant reason that affects workers' hazard recognition performances and induces human errors [8–10]. If the workers do not have to possess the required schemata to be applied in potentially hazardous situations, they may be susceptible to injuries and fatalities. In order to enhance workers' perception of risk and hazards within the construction environment, as well as to reduce unsafe risk-taking behavior, workers are often put through safety training interventions. Through these training programs, the workers are trained to actively gather information necessary to identify conditions that are precursors to the potentially unsafe conditions.

However, despite the efforts to improve safety performance through safety training, the construction sector still accounts for disproportionate injury rates [11]. In this regard, measuring the effectiveness of assorted styles of safety training helps to create an effective training method. In particular, finding avant-garde ways to objectively and accurately measure the effectiveness of various aspects of construction training on the risk-taking behaviors of workers on the job site would allow for a more systematic avenue to tailor optimal construction safety training methods. Despite the potential importance of training and their evaluation strategies, few have been identified in the literature, and there is yet to be an organized effort to systematically investigate and analyze the current techniques. This paper, therefore, aims to contribute to the current body of knowledge by providing a systematic review of the available literature to identify and assess conventional safety training approaches, their evaluation strategies and suggest possible research directions. The results of this study can be used by practitioners to strategically identify the potentially ubiquitous safety training program to create an optimal construction environment.

2. RESEARCH METHODOLOGY

A systematic review was conducted to introduce and investigate the current methods of construction safety training as well as techniques to evaluate the effectiveness of the training. To achieve a target and structured review of the literature, the journals that deal with the subject were selected in two steps. In the first step, an exhaustive search was carried out on the following databases: ASCE Library, Scopus, Google Scholar, IEEE Xplore, Taylor, and Francis Online, Science Direct, and Web of Science. Several keywords such as "Construction," "Safety," "Training," "Virtual Reality," "Augmented Reality," "Visualization," "Hazard Behavior Analysis," "Risk Perception," and "Evaluation" were considered so that the search could cover a broad range of related disciplines. This round of search identified most related articles from several journals, including but not limited to Advanced Engineering Informatics, American Journal of Industrial Medicine, Applied Ergonomics, Automation in Construction, Construction Management and Economics, Ergonomics, International Journal of Engineering Education, International Journal of Environmental Research and Public Health, Journal of Information Technology in Construction, Journal of Computing in Civil Engineering, Journal of Construction Engineering and Management, Safety Science, Virtual Reality and Construction Safety, and IEEE Transaction on Biomedical Engineering, as well as conference proceedings, including ASC Annual International Conference Proceedings, and Construction Research Congress. Publications that did not

comprise the keywords mentioned above in their titles or abstracts were screened out in the second step. In addition, irrelevant papers were filtered out after a brief visual examination of the content of the papers. Consequently, 45 of the most relevant papers within the scope of this study were selected for further analysis, as shown in Table 1. Figure 1 denotes the distribution of selected publications by years.

Table 1. Distribution of Articles by Findings

Findings of Research	Authors
Construction safety training methods	
• Traditional safety training methods	Lee et al., 2003 [12]; Williamsen., 2003 [13]; Halperin & McCann, 2004 [14]; Forck, 2005 [15]; Burke et al., 2006 [16]; Wallen & Mulloy., 2006 [17]; Choudhry & Fang., 2008 [5]; Cherrett et al., 2009 [18]; Dong et al., 2009 [19]; Li et al., 2012a [20]; Olson et al., 2016 [21]; Jeelani et al., 2017 [22]; R. Eiris Pereira et al., 2019 [23]
• Virtual reality-based safety training methods	Hadipriono & Barsoum, 2002 [24]; Hsiao et al., 2005 [25]; Wang Xiangy, 2007 [26]; Ku & Mahabaleshwar, 2011 [27]; Dickinson et al., 2011 [28]; Guo et al., 2012 [29]; Li et al., 2012b [30]; Sacks et al., 2013 [31]; Kleiner, et al., 2014 [32]; Bhoir & Esmaeili, 2015 [2]; R Eiris Pereira et al., 2017 [33]; Lin et al., 2018 [34]; Gao et al., 2019 [35]; Jeelani et al., 2020 [36]
• 360-degree panorama-based safety training methods	Jeelani et al., 2017 [22]; Eiris et al., 2018 [37]; Pham et al., 2018 [38]; Pereira & Gheisari, 2019 [39]; R. Eiris Pereira et al., 2019 [23]; Eiris et al., 2020 [40]
Construction safety training evaluation techniques	Teo et al., 2005 [41]; Guo et al., 2012 [29]; Li et al., 2012b [30]; Ruttenberg, 2013 [42]; Kleiner, et al., 2014 [32] ; Jeelani et al., 2017 [22]; R. Eiris Pereira et al., 2017 [33]; Lin et al., 2018 [34]; Eiris et al., 2018 [37]; Pham et al., 2018 [38]
Potential of physiological monitoring for evaluation of safety training	Poh et al., 2010 [43]; Hwang, Seo, Jebelli, et al., 2016 [44]; Hwang, Seo, Ryu, et al., 2016 [45]; Wang., et al., 2017 [46]; Hwang & Lee, 2017 [47]; Jebelli et al., 2017 [48] ; Jebelli, Choi, et al., 2018 [49]; Jebelli,et al., 2018 [50]; Hwang et al., 2018 [51]; Jebelli et al., 2019 [52]; Choi et al. 2019 [53]; Habibnezhad et al., 2020 [54]

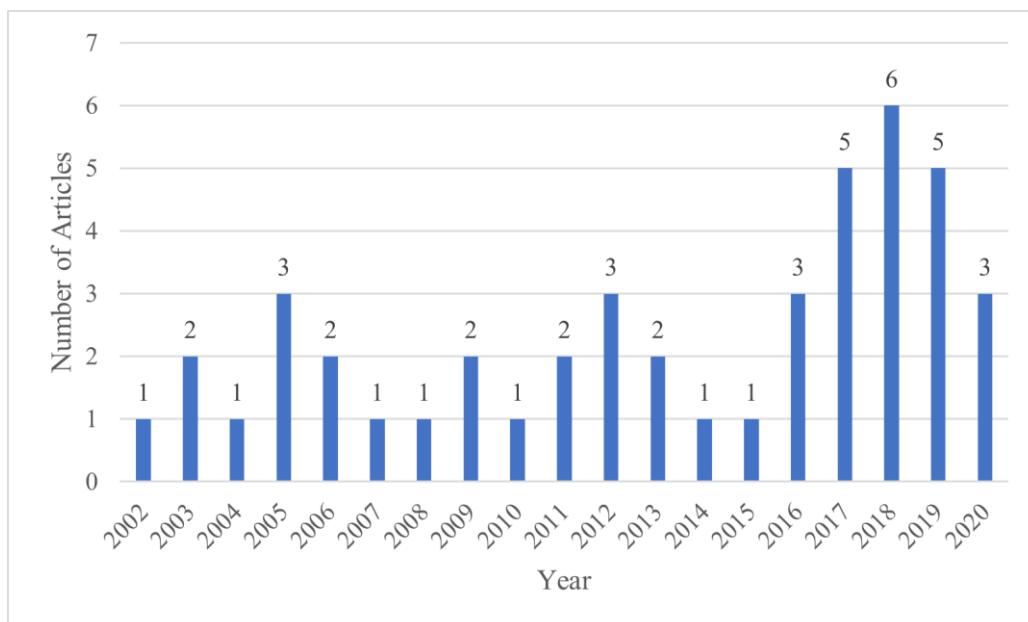


Figure 1. Publication distribution by years

3. RESULTS

3.1. Construction Safety Training

3.1.1. Traditional safety training methods

Safety training provides knowledge to the workforce to help reduce the injuries and fatal accidents on construction job sites [12,14,17,19,22,23]. Within current industry practices, safety training programs are offered to equip workers with detailed hazard information, safe behavior, and proper practices in a construction worksite. Much of the motivation for adopting these training efforts is to increase compliance with occupational safety and health rules and regulations [20]. Traditional safety training programs are usually lecture-based sessions that use multimedia contents, such as images, videos, slide presentations, or pamphlets [15]. As per the dynamic and hazardous nature of construction workplaces, safety training usually takes place in an off-site setting. In this regard, two-dimensional images and videos are employed to assist trainees in visualizing complicated construction scenarios. However, trainees cannot interact with images and videos and suffer from low levels of engagement due to the one-directional reception of material, which may translate to reduced learning by trainees [16]. To address this issue, interactive forms of training through discussions and toolbox talks have been employed to provide elevated hands-on learning [13,21]. However, the effectiveness of such hands-on training methods may vary given numerous influencing factors at construction sites, including the attitudes of the workers, the natural or trained cognitive abilities of the trainees, and the communication skills of the trainer and the trainees. Moreover, these methods cannot fully convey the dynamics found in real-world job sites [18]. These limitations innate in the current safety training approaches may be attributed to the inefficiency of the current methods to instill the complexity involved in a typical construction project.

3.1.2. Immersive environment-based safety training methods

Immersive environment-based training systems are very useful to train individuals in an environment that is risk-free and allows users to learn without real adverse consequences. Researchers have shown that training in an immersive environment would result in marked increase in technical skills, knowledge, as well as self-reported confidence and comfort [31,35]. In addition, retention of the experiential knowledge from training in a simulated immersive environment is pivotal in augmenting the hazard recognition and risk perception skills of the workers [26,31]. As such, safety training in the immersive digital environments has the potential to enhance training experience, eliminate or reduce health and safety risks, and in turn, induce safe behavior on construction job sites. In recent years, technological advancement has empowered researchers and practitioners to create immersive digital training environments mimicking the complexity of the real construction environment. These immersive environment-based safety training methods can be divided into two types: virtual reality-based safety training and 360-degree panorama-based safety training.

3.1.2.1. Virtual reality-based safety training methods

Virtual Reality (VR) technology can create immersive training environments that provide learners with experiential learning opportunities. These digital environments can visually replicate hazardous conditions that are impossible, dangerous, or expensive to experience in construction jobsites. This lifelike simulation has the potential to provide the workers with an immersive medium to visualize and interact with potential safety risks. In this context, researchers have devised a fair share of VR systems offering construction safety training. For instance, Albert et al. developed a high-fidelity virtual environment to immerse the workers in different working scenarios and assess their hazard recognition skills [32]. Hsiao et al. used Cave Automatic Virtual Environment (CAVE) system to simulate the scaffolding work and evaluated the impact of the platform height, platform width, and working groups in the risk perception of the participants [25]. Likewise, researchers have used interactive virtual environments for the safety training of the workers for scaffolding work [24,27] and tower crane operations [27].

Virtual reality enables trainees to explore the environment at their own pace and allows them to have control over their progress. Besides, optimizing the learners' experience during the learning process in a virtual environment can result in a paradigmatic shift in attentional allocation, engagement, and concurrently, knowledge retention [55,56]. In this regard, studies have often combined VR and gaming technology to create authentic, meaningful tasks and activities for construction education. As such,

researchers have developed serious VR games to stimulate deeper learning, promote student interaction, and allow better situational awareness. For example, Dickinson et al. developed a serious VR game on trench safety education, which included fall, struck-by, and caught-in hazards [28]. Likewise, Lin et al. developed a 3D serious game allowing users to fill the role of safety inspectors, and in turn, evaluate their hazard identification skills [34]. While most VR-based training systems are single-user, several researchers have developed multiuser virtual environments that enable multiple people to collaborate in the same environment [29,30]. This approach enables users to understand the significant impact the decision making of an individual has on overall safety and wellbeing at a construction site. In addition, trainees can interact with other people to find out the best collaboration approach. In this vein, Guo et al. developed a highly collaborative VR safety training system that allowed several trainees to perform construction plant operations within a virtual environment [29]. Similarly, Li et al. developed a multiuser VR training program to allow trainees to learn and practice safe crane dismantling procedures [30].

In contrast to traditional safety training methods, VR-based safety training can be regarded as an effective approach to provide experiential safety knowledge in various hazardous situations without potential harm. However, several limitations have hindered the full adoption of VR technology as a standard method for providing safety training in the construction industry. Creating close-to-reality virtual settings of a dynamic construction environment to achieve a faithful representation of the actual world is time-consuming [33]. Moreover, the rendering required for the realistic representation of the scenes of congested construction settings entails high computational cost [2,31].

3.1.2.2. 360-degree panorama-based safety training methods

To address the limitations of time and computational cost related to developing an immersive virtual environment, the 360-degree panorama has been explored in the construction industry [39]. 360-degree panorama utilizes photography and videography to generate true-to-reality surrounding views of the construction environment. As such, the generated unbroken view of the surrounding creates a highly engaging and immersive experience due to the realism embedded in the photography and videography data. Since the 360-degree panorama utilizes digital imaging techniques, lower computational power is required to represent the jobsite. Thus, the low computational cost, ease of capture, and non-computer-generated simulation are the advantages of such a technique over the traditional VR-based safety system. Furthermore, the interactive exploration and visualization, and the capability of adding layers of information over the obtained data make the 360-degree panorama useful for hazard recognition in safety training [39]. In this regard, the 360-degree panorama has been used by researchers in the construction domain to improve the hazard identification and situational awareness of the workers. For example, Jeelani et al. used 360-degree panoramic images for simulating personalized accidents to train construction workers [22]. This study evaluated the sense of the presence of workers in a series of safety scenes. Likewise, Eris et al. captured a series of active job sites using the 360-degree panorama technique to develop a safety training environment [23]. This system allowed users to navigate throughout the construction site and evaluated the fall-hazard identification of the workers. Eris et al. conducted a similar study to evaluate the focus-four hazard identification capacity of the workers [37]. In another study, Pham et al. utilized a 360-degree panoramic technique to develop a learning system for enhancing safety education amongst the students [38]. The developed system allowed students to virtually visit a construction site to identify hazards in digital locations.

Although, 360-degree panorama offers an immersive experience due to the realism innate in the photography and videography data, several limitations regarding image quality, static vantage point and stitching parallax still exists [39]. Such limitations hinder the optimal implementation of 360-perspective based safety training method for practical application in construction jobsite.

3.2. Construction Safety Training Evaluation Techniques

Safety training is one of the most common interventions to improve hazard recognition and workplace safety. The evaluation of the workers' perception towards safety training programs, in terms of clarity, knowledge acquisition, relation to practice, and purpose achievement, is a key step in identifying the effectiveness of such programs. In this regard, questionnaires are shown to be an efficient way to analyze the workers' attitude and reception of the training program. Questionnaires can be structured to elicit perceptions of multiple aspects of safety training. Also, trends and patterns can be identified through questionnaires to uncover the limitations of the training program. In this context, Teo et al. used questionnaires to identify issues regarding safety training at active construction sites [41]. In another

study, Lin et al. used a list of questionnaires to determine the effectiveness and suitability of the training programs [34]. Similarly, Guo et al. leveraged questionnaires to assess the performance of a designed VR-based safety training platform compared to the traditional approach [29]. Likewise, Li et al. evaluated the effectiveness of a multiuser VR training platform using questionnaires [30]. As such, the trainees participated in a survey concerning the training process after safety training sessions.

The ability to identify potential hazards is essential to indulge in safe behavior and achieve a safe construction environment. One of the important goals of safety training programs is to improve the hazard recognition skills of the workers, as unrecognized hazards can potentially result in undesirable workplace accidents and injuries. In this regard, the effectiveness of the training platform has been assessed by evaluating the hazard recognition performance of the trainees. In a study completed in May 2013, the behaviors of workers on-site were monitored before and after receiving OSHA 10-hr training. The evaluation suggested that OSHA 10-hr training significantly augment the hazard recognition performance of the workers [42]. In another study, Albert et al. evaluated the effectiveness of a high-fidelity virtual training environment by measuring its impact on workers' hazard recognition skills in different working scenarios [32]. Likewise, to evaluate the 360-degree panorama-based safety training method, Jeelani et al. compared the hazard recognition performance of the workers in pre-intervention and intervention phases [22]. The pre-intervention data provided an initial estimate and variability of workers' hazard-recognition ability prior to the intervention. The evaluation between the pre-intervention and intervention phases suggested that the intervention was effective in improving the hazard recognition performance of the workers.

Researchers have also combined both questionnaires and hazard recognition skills to assess the effectiveness of safety training platforms. For instance, to evaluate the usability and function of the 360-degree panorama-based training method for hazard identification and user satisfaction, researchers collected data from hazard identification test and post-test survey [23]. In the hazard identification test session, four different panoramic images, containing all the information trainees were expected to learn, were shown as interactive augmentations. In this session, trainees were required to actively explore the panoramic location to learn about the fall hazard. Following that, trainees were shown sequential panoramic images without any interactive augmentations and were required to identify all fall hazards. Data collected within the developed platform was used to evaluate the hazard recognition ability of the trainees. Besides, a post-test survey (i.e., questionnaire) was used to evaluate platform usability.

Although safety training evaluation has led to significant findings, construction practitioners and researchers have mainly relied on questionnaires and hazard recognition ability to assess the effectiveness of the training platforms. Such a subjective understanding of workers' attitude and ability is insufficient and prone to biases. In addition, these methods are unable to show changes in workers' perception of various safety risks overtime during the training. In this regard, the conventional methods of evaluating safety training approaches may not be efficient to comprehend workers' perception of safety risks, resulting in inadequate learning outcomes.

3.3. Potential of Physiological Monitoring for Evaluation of Safety Training

Given the deficiencies of safety training evaluation techniques, there is an increased need for objective and non-intrusive methods to continuously assess workers' perceived risk. To fill this gap, the continuous and quantitative assessment of 'trainees' perceived risk using physiological responses (e.g., cardiac activity, electrodermal activity, brainwave activity) acquired from wearable sensors (e.g., wristband, headset) can be an effective alternative to objectively evaluate the effectiveness of the safety training approaches. Physiological responses to an external stimulus can offer valuable information about an individual's health as well as the physical and mental state [47,50,54]. For instance, when an individual is in a highly stressful environment, the brain innervates the heart via the sympathetic nervous system. This change in the heartbeat (HB) mechanism results in variations in blood volume; these can be measured by using electrocardiography (ECG) and photoplethysmography (PPG) [44,45]. As such, the monitoring of workers' cardiac activity through noninvasive wearable sensors can help recognize the stress level of the workers throughout the training across different environments. In this case, it is important to monitor the workers in both the controlled training and the actual work environment to evaluate the risk perception of workers. Likewise, if the sympathetic branch of the autonomic nervous system is stimulated by external stressors, the number of active sweat glands increases, reflecting a higher Electrodermal activity (EDA) measurement [43]. In this vein, EDA can be a reliable metric to understand the perceived risk because perceived risk stimulates the sympathetic nervous system [53]. As such, noninvasive monitoring of EDA can give an objective understanding of the risk perception of

workers performing training across different environments. Similarly, Electroencephalogram (EEG) has been widely used to record the changes in brain activity from diverse mental status (i.e., attention, emotion, cognitive load, etc.) [48,50–52]. The evaluation of the reflection of various stressors on brain activity is a reliable way to assess the risk perception ability of the workers [46,51]. In this regard, monitoring of the brain activity through noninvasive wearable EEG can provide an objective understanding of the perceived risk of the workers throughout their training in various environments.

4. RECOMMENDATIONS

Through the conducted literature review, various safety training approaches in the construction sector were identified. Lecture-based sessions and toolbox talks can be regarded as traditional training methods that are carried out in off-site and on-site settings, respectively. Immersive environment-based safety training methods are alternative approaches incorporated into the construction safety education to address shortcomings of traditional methods, such as the limited hands-on experience. However, currently, there is a lack of immersive training platforms in practice due to technical barriers. Future research is required to develop a more intuitive and seamless immersive experience, particularly for hazardous construction operations.

Moreover, prevalent safety training evaluation techniques were recognized in this literature review. Referring to the limitations of such techniques, the need for an alternative approach was indicated in this study. Thus, the potential of physiological monitoring of construction workers for assessing their perceived risk was introduced and highlighted. It is recommended that future research focus on the integration of physiological monitoring of workers and safety training as a means of providing reliable evaluative safety training platforms. In this regard, employing immersive virtual training platforms with a higher level of engagement is suggested. By investigating different physiological responses and acquiring appropriate metrics, further insights regarding the potential application of physiological monitoring for training evaluation can be achieved.

5. CONCLUSION

This study synthesized the current body of knowledge on methods of construction safety training and techniques for measuring the effectiveness of safety training. The paper identified and analyzed various safety training approaches aiming at enhancing workers' risk perception and hazard recognition ability. The review found that immersive environment-based safety training has a considerable advantage over the traditional method of safety training. Similarly, the review also presented the attributes of the conventional evaluation techniques of safety training. In this regard, it was found that current methods of evaluation are noncontinuous, intrusive, and prone to bias. The paper offers an alternative method of objective evaluation of the effectiveness of safety training programs through noninvasive, continuous physiological monitoring of the trainees during the training. Considering the feasibility of the physiological responses to evaluate the workers' risk perception, future research is required to assess the ability of physiological monitoring in immersive environment-based safety training approaches. The findings of this research can create avenues to develop promising training strategies by objectively evaluating them to determine the most effective approach for widespread implementation in the construction industry. Such an effective training method will augment the workers' risk perception and hazard recognition ability and will eventually allow the construction job sites around the world to operate at a safer capacity.

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VIII. PRACTICE IN CONSTRUCTION MANAGEMENT (C2)

Advanced Work Packaging (AWP) in Practice: Variables for Theory and Implementation

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Abstract: Diversification of project delivery methods (PDM) under ever-changing construction business environment has significantly changed the role of project participants. Active efforts to effectively sharing the roles and responsibilities have been observed in the project management offices (PMOs) among owner/operator organizations as well as engineering, procurement, construction and maintenance (EPCM) firms. In order for being effective in a holistic way throughout the project life-cycle, a PMO needs to have ‘adequate management skills’ as well as ‘essential technical capabilities’ in cooperating with many different participants. One of the well-known examples of the PMO’s tool to support these skills and capabilities is the effective ‘work packaging (WP)’ that serves as a common basis integrating all relevant information in a structured manner. In an attempt to enhance the construction productivity, the concept of ‘advanced work packing (AWP)’ has been introduced by Construction Industry Institute (CII). The AWP enables productivity to be improved by early planning of construction packages in the design phase “with the end in mind”. The purpose of this study is to identify and evaluate the ‘variables’ of advanced work packing (AWP) for life-cycle information integration. Firstly, an extended concept of advanced WP based on the CII AWP was defined in order to comprehend many different issues of business functions (e.g. cost, schedule, quality, etc.). A structured list of major components and variables of AWP were then identified and examined for practical viability with real-world examples. Strategic fits and managerial effectiveness were stressed throughout the analyses. Findings, implications and lessons learned are briefly discussed as well.

Key words: advanced work packaging (AWP), work package (WP), information systems

1. INTRODUCTION

The traditional role of project participants under diversifying project delivery methods (PDM) has changed dramatically. Several business tasks are currently shared among different participants, and new forms of integrated tasks are utilized in order to improve project performance in many different terms.

One of best examples of the changes is the ‘construction planning for field installation’. It has been a traditional process of a general contractor. Nevertheless, as previously stated, a concept for conveying the roles and responsibilities of this task to the engineering firm and also, in part, to the owner was developed as a global best practice (Lee et al. 2005; CII 2015).

The concept of ‘advanced work packing (AWP)’ was introduced by Construction Industry Institute (CII), which enables productivity improvement by early planning of construction packages in the design phase “with the end in mind” (CII 2013).

Sharing roles and responsibilities for an AWP implementation may require additional tools and methods to accomplish this task among project participants. In this sense, the purpose of this study is to identify and evaluate the ‘variables’ of advanced work packing (AWP) for life-cycle information integration. The extended concept based on CII AWP was defined first in order to comprehend many issues of relevant construction functions. A structured list of major components and variables of AWP were then identified and examined for practical viability.

2. INFORMATION OF ADVANCED WORK PACKING (AWP)

CII (2013) introduces AWP as “one practice in the project management toolkit that improves project delivery effectiveness and predictability”. “AWP is the overall process flow of all the detailed packages including construction work packages (CWP), engineering work packages (EWP), and installation work packages (IWP)” and “providing a structure focused execution planning that is directed at the construction workface” (CII 2013).

As summarized in Table 1, EWP, CWP, and IWP contain detailed technical as well as management information. It is noteworthy that the information in detail is further journalized by each package. For example, bill of materials (BOM) items for ‘concrete’ need to be prepared based on each package with a locator such as ‘quantity of concrete for a foundation for pump station’. All information contained in the AWP package must be decomposed according to the required physical breakdown by the project. However, the relevant legacy systems usually do not maintain detail breakdown items.

These AWP data requirements involves many issues in information exchange (IE) for implementation. First, hierarchical information integration between different levels of detail is required among different organizations (e.g. integration between BOM data, cost data, and accounting data), including the integration issue in-between 3D-CAD graphic data and non-graphic databases. Secondly, AWP encompasses many construction business functions such as design, technical specifications, cost, schedule, procurement, and others. It is another challenge to implement AWP in practice because of the complex mapping mechanism.

Table 1. AWP contents summarized by Haggard (2015) based on CII (2013)

AWP packages	Example of information included
EWP (Engineering AP)	Scope of work, Document list, Drawings, Specs, Vendor data, BOM, Equipment list, Permits
CWP (Construction WP)	Safety requirements, At least one EWP, Schedule, Budget, Environmental requirements, Quality requirements, Permits
IWP (Installation WP)	Quantity work sheet, Safety hazard analysis, Specific tasks, Material safety data, Drawings, Specifications, Change documents, Manufacturer's installation instructions, Model shots, BOM, Required tools, Installation test result forms, As-built documents, Inspection check lists, Completion verification

For each project, AWP can be implemented differently from others, as each one has distinct managerial requirements. Nonetheless, automated information exchange (IE) is essential for successful implementation of AWP concept for all, especially for capital projects. In relation to organizational issues, the project management office (PMO) shall facilitate the exchange of this information among many project participants in for effective AWP management. A PMO can be an owner, a professional project manager, an engineering firm, an engineering / procurement / construction (EPC) firm, or a general contractor (GC). It implies that the issue of incorporating intra- organizational and inter-organizational barriers to information flow under different project delivery methods needs to be examined.

In order to address this issue, this paper attempts to define the AWP variables in a structured way. It is defined in this paper that “*effective AWP requires a life-cycle integration of 3D-CAD, AWP repository, and legacy systems among project participants supported by information exchange standards to ensure the interoperability, connectivity, and flexibility*”.

3. VARIABLES FOR AWP SYSTEM IMPLEMENTATION

As stated in Section 2, for the purpose of exploring issues of effective AWP implementation in practice, the structured variables of AWP were developed as listed in Table 2. The four dimensions of these variables include project life-cycle, construction business function, computer system, and standards for information exchange.

Table 2. Variables of AWP implementation

Dimension	Variable	Constituents
Life-cycle	Phase	Planning, Design, Procurement, Construction, Startup, O&M, Disposal
Function	Business function	Fourteen construction functions defined by Jung & Gibson (1999)
System	3D-CAD	Authoring, Viewer, Simulation
	AWP Repository	Historical data, Template, Procedure
	Legacy	ERP, MIS, PMIS
Standards	Numbering	WBS, EWP, CWP, IWP
	Information	Format, Property, Process, Ontology

3.1. Life-cycle

The first dimension of the AWP implementation is the *project life-cycle*, focusing on data handover requirements along with different phases under different project delivery methods. The phases of life-cycle is defined as ‘planning, design, procurement, construction, startup, O&M, and disposal’. As previously discussed, the AWP development process begins in the early stage of design phase with the joint efforts of the engineering firm, EPC firm, and the owner organization.

3.2. Function

Secondly, the core *function* of AWP is to plan ‘construction work for field installation’ that involves many relevant construction business functions such as cost management, scheduling, quality, safety, procurement, and so on. The fourteen construction business functions defined by Jung and Gibson (1999) are used in this study, including “planning, sales, design, estimating, scheduling, materials management, contracting, cost control, quality management, safety management, human resource management, financing/accounting, general administrations, and R&D”.

3.3. System

The third dimension is the *system* architecture of the AWP application as depicted in Figure 1. There are mainly three groups of systems; ‘3D-CAD, AWP repositories, and legacy systems’ (Jeong and Jung 2019). The first group of ‘3D-CAD’ systems includes BIM authoring, viewer, and simulations tools. Many AWP requirements by the owner mandate the use of a 3D-CAD system to visualize the IWP as a three-dimensional drawing, but it is advisable to utilize the 3D-CAD system selectively because it requires much engineering and managerial overhead effort.

The following group of ‘AWP repository’ is the key component that archives and handles AWP structure, data, templates, and procedures. The third group of ‘legacy’ systems consists of Enterprise Resource Planning (ERP), Management Information System (MIS), and Project Management Information Systems (PMIS).

Legacy systems cover a wide range of construction business functions including cost, schedule, quality, procurement, etc., while the 3D-CAD systems manipulate graphic objects with technical data. The AWP repository system connects and allocates data between 3D-CAD systems and legacy systems.

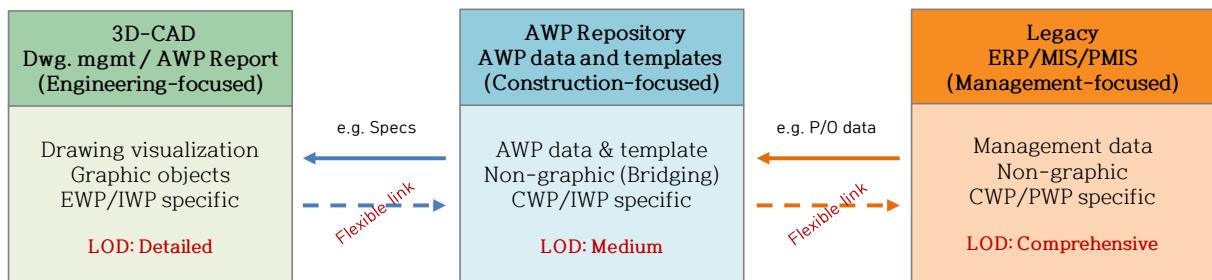


Figure 1. Components of AWP application systems

3.4. Standards

Finally, the fourth dimension is about the *standards* issue of information exchange (IE). AWP data are shared across several different organizations throughout the project life-cycle. Therefore, machine-to-machine information exchange is a critical issue in implementing AWP in practice. This study identified two major variables of AWP IE standards. One is the ‘numbering’ standards and the other is ‘information’ standards.

The AWP ‘numbering’ standards refers to predefined and machine-readable numbers, titles, and rules for numbering Work Breakdown Structure (WBS), EWP, CWP, and IWP. These numbering standards need to be flexible enough (Jung and Woo 2004; Jung and Kang 2007) in order to customize the level of detail required for different projects. The ‘information’ standards define the formats, properties, processes, and ontologies for interoperable data transactions.

Numbering standards coupled with information standards enable AWP information exchange (IE) without human intervention while keeping the interoperability, connectivity, and flexibility for managerial effectiveness.

4. ISSUES OF PRACTICAL AWP IMPLEMENTATION

The variables identified for AWP implementation are discussed in Section 3. A series of workshops with experts in the area of AWP practice were held, and many issues were actively discussed based on these variables. Three issues include standards making, flexible AWP structure, and shared roles and responsibilities (R&R) are briefly introduced in this paper.

4.1. Standards making initiative

AWP documents will be prepared and used by many organizations. Therefore, it is desirable that one of the project participants shall lead and publish the policies, procedures, and standards at an early stage of the project. One of the problems that arise under a design-bid-build (DBB) contract is that a general contractor cannot have the opportunity to participate in CWP development. This situation requires additional efforts in reconfigure AWP data into the construction phase. As many owners mandate the AWP implementation in their projects, they are accountable for making standards for their projects. For owners who do not have the technical capability to prepare standards, it is recommended to invite one firm from the EPC service providers in the early engineering phase to set up standards. The quality of AWP contents is another issue that should be addressed among project participants. From the industry perspective, global standards can facilitate AWP data handover among unspecified owners as well as unspecified EPC service providers.

4.2. Flexible AWP structure

A rigid breakdown structure with a fixed numbering scheme cannot accommodate AWP requirements in terms of life-cycle, function, and system variables listed in Table 2, however, it is much easier to computerize. In order to address this issue, a concept of flexible work breakdown structure was proposed by Jung and Woo (2004). A flexible AWP structure with a standardized numbering system for WBS, EWP, CWP, and IWP can use different levels of work packages (e.g. concrete work for a footing vs. concrete work for a group of footings) in a standardized way (Jung et al. 2013). This issue is particularly significant for engineering firms and general contractors because it is necessary to accumulate AWP experiences into a structured knowledge database. Without having this knowledge database, developing and maintaining AWP documents repeatedly for a capital project would be a burden for the project engineers as well as information systems managers.

4.3. Shared roles and responsibilities (R&R)

In the AWP application, the construction work plan for field installation is developed by the engineering firm and general contractor before the specialty contractor may be invited to the project. Indeed, the specialty contractors are those with a direct role and responsibility (R&R) on site installation. This fact means that a specialty contractor may present a dispute against the engineering firm and general contractor for a damage possibly caused by the work plans. In other words, shared R&R for site installation creates a complex legal situation. Shared R&R also affects the contract amount between the owner, the general contractor, and the specialty contractor. One of the goals of implementing AWP is to improve productivity. This economic benefit of productivity improvements through AWP are verified

by case-study presented by CII (2013; 2015). Sharing benefits with R&R sharing can be a challenge in implementing the AWP concept and these considerations must be thoroughly examined by all parties.

5. CONCLUSIONS

AWP is a promising concept, and it organizes the construction work planning process with advanced tools in order to improve construction performance in terms of cost, schedule, and quality. AWP changes existing practices by sharing roles and responsibilities among owners, designers, and contractors. Another meaningful aspect of AWP is the accumulation and transformation of construction experience and knowledge into a structured database. In order to implement this promising concept in a real-world project, it is essential that information is seamlessly exchanged within the organization and between the organizations.

To this end, the purpose of this paper was to identify the practical variables of the AWP implementation. This study concluded that “an effective AWP requires a life-cycle integration of 3D-CAD, AWP repository, and legacy systems among project participants supported by information exchange standards to ensure the interoperability, connectivity, and flexibility”.

This definition discusses seven variables that have been identified, including life-cycle ‘phase’, construction business ‘functions’, ‘3D-CAD system’, ‘AWP repository’, ‘legacy system’, standard ‘numbering’, and standard ‘information’. These seven variables were grouped into four dimensions and further decomposed into thirty-eight constituents to represent the relationships.

The proposed variables in a structured manner were used to organize and discuss the practical issues of implementing the AWP concept in capital projects. A series of workshops were held with experts in the area of AWP practice, and many issues were actively discussed. This paper provides a summary of selected issues, such as ‘standards making initiative’, ‘flexible AWP structure’, and ‘shared roles and responsibilities’.

Findings of this study indicates that the global standards for AWP data interoperability can facilitate the active implementation of this promising concept. It has been also found that any type of AWP standards (for a project or an organization) must be flexible enough to control the levels of detail of the work packages. Finally, sharing roles and responsibilities (R&R) when developing construction site work plan can have a significantly impact on contractual and legal relationships between the owners, engineers, contractors, and especially specialty contractors.

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Claim Management Process of General Contractors in South Korea

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Abstract: The purpose of this study is to investigate the current status of claim management process of general contractors in South Korea. As the claim management becomes more important nowadays, maintaining the process for claim management systematically and consistently becomes more important as well. To improve the claim management process, it is necessary to diagnose the current status of claim management process so companies establish their targets for improvement. This study develops a survey to identify the current status of claim management process that major general contractors in South Korea have. Questions in the survey are classified into four categories including entitlement check, potential claim event check, time bar check, and tasks for substantiation. By conducting a series of statistical analyses with 94 survey data collected from employees working in the general contractor companies in South Korea, this study examines and analyzes their claim management process in terms of the several categories. It is expected that the results contribute to diagnosing how practitioners maintain their claim management, which will help them establish the direction of management enhancement.

Key words: Construction claim, Claim management, Contractor's view, Work process, Survey research

1. INTRODUCTION

Construction projects have experienced more claims unexpectedly during their delivery as construction projects become larger and more complex. Unlike other products in various manufacturing industries, construction projects take place through a variety of participants with non-recurring processes. There are many stakeholders, such as client, architect, general contractor, subcontractors, vendors, and consultants, being involved for a construction project. Since they are different business entities, they have their own interests and their business processes are different substantially. Thus each construction project is unique, project stakeholders' processes need to be somewhat customized to reflect the project characteristics. Due to these, construction claims are inevitable in the construction industry. Claims are commonly occurred because of the inherent risks of long duration, various uncertainties and risks, and complex relationships amongst stakeholders with different and often competing interests [1].

Contract management has become more important as it is one effective way to minimize claims. In accordance with this tendency, many major construction companies recognized the importance of claim and contract management. While they created internal business processes taking various preventive measures, most of them are just nothing more than a cursory rule [2]. Many previous studies have been conducted regarding the construction claims, but most of them have focused on the causes of claims and developing the management model [3, 4].

This study investigates the status of claim management process from the perspective of general contractors in South Korea. Benchmarking is a systematic process of measuring and comparing a performance against that of other in key business activities [5]. In order to achieve the continuous improvement from the benchmarking process, it is necessary to diagnose the current status of a company on certain aspects so it can establish its targets for improvement. As mentioned previously, while many studies about claims have focused on the causes of claims and management model development, the current body of knowledge lacks how practitioners actually conduct the claim management. This research examines the current claim management process from the contractor's point of view in South Korea. For this, this study develops a survey to diagnose the current status of claim management process. Questions in the survey are classified into four claim management functions; entitlement check, potential claim event check, time bar check, and tasks for substantiation, which are mentioned as key work functions during the survey design. How the major contractors in South Korea execute claim management in terms of the four work functions is presented. In addition, the claim management by industry sector is investigated as well.

2. LITERATURE REVIEW

Claims have had significant impacts on construction projects. Arcadis (2018) reported that global construction disputes cost \$43.4 million US dollar and last 14.8 months on average [6]. Based on the statistical data from United States and Canada, 50% of claims constituted an additional 30% of the original contract price and in some cases the claim values were as high as the original contract price [7]. In addition to this quantitative values, claim management has been included as one of the most important project management factors [4]. Overall, the claim management is one important managerial area that cannot be ignored in the construction industry.

The importance of claim management has been grasped and many previous studies related to claims have been conducted. These studies have been carried out in two main aspects. First, there have been many studies analyzing the causes and risks of claims based on the case studies, interviews, and surveys. To investigate this theme, some of the research studies investigated common mistakes and causes of construction claim [1], [8–10]. Second, many studies have been conducted on predicting contract risks causing claims and developing the evaluation models. Those research studies generally aimed to make process models representing different types of claims [11]. For this topic, there have been also many attempts to develop a process framework regarding the construction contractor's claim work [2, 12]. This type of studies suggested strategies to avoid or mitigate the predicted construction claim, and recommended the management focus on controlling those issues.

These previous studies carried out overall analyses about the current claim issues in the construction industry based on case studies or questionnaires. However, to improve the process for better performance, it is important to be able to diagnose the current status of claim management process [13]. Unfortunately, few studies have investigated this topic. So this research aims to measure and compare the status of key business activities in the claim management process. The claim management process may vary by industry sector as different sectors have different level of project complexity and budget for managing projects. For example, by using project-level data, Yun et al.(2016) compared the management efforts by industry sector and found that the infrastructure sector made less commitment to project management than building and industrial sectors [14]. In addition, Vldogah and Ndekugri (1997) found that civil engineering contractors are more likely to pursue claims compared to building engineering contractors [15], which infers that the claim management process can be different by industry sector.

This research aimed to investigate the status of claim management process across the construction industry. After investigating the overall claim management process by four work functions, this study compares them by industry sector as well.

3. SURVEY DESIGN

This study developed a survey asking the degree that respondents agree on certain work elements related to the claim management processes. Table 1 shows an example. As shown in the table, respondents have five choices for a certain statement.

Table 1. A Survey Question Example

NO	Question	Response				
		Strongly Disagree ①	Disagree ②	Neutral ③	Agree ④	Strongly Agree ⑤
Q1	The database of claim issues is maintained by and shared among claim managers and staff in relevant departments.					

The survey has 20 work elements which represent four major functions. Based on the literature review and industry expert interviews, this study considered four core work functions for claim management as follows.

(1) Entitlement Check

Once a claimable event occurs, it is necessary to check whether the event is eligible for entitlement or not. The work elements in this work process are about recognizing the exact contractual status and site condition. Thus this category contains work elements regarding claim logs of previous cases in company, preliminary education of relevant department, and appropriate interpretation regarding the contract. Mitropoulos and Howell (2001) argued the critical factor of dispute is checking about project uncertainty and contractual problem [16]. Checking project and contractual condition is often mentioned as the key factor which develop the claim in project [8, 17]. So, if the related participants miss the work process regarding the entitlement check, then the claims would not be submitted even though the claimant is sufficiently entitled.

(2) Potential Claim Event Check

In order to proactively prevent claims, all of the potential claimable events on site have to be monitored. The early involvement of management regarding claim event has positive influence to resolve the dispute [18]. So this category contains works which ask the effective monitoring of newly occurred events and sharing system. Love et al. (2010) asserted that the contractor should identify the circumstances arising from the situation of the project and it is a main underlying condition for claim [3]. Yates and Epstein (2006) also emphasized early recognition of potential delays to minimize the delay claim [19].

(3) Time-bar check

The work elements in the time-bar check work process are to keep the time-bar deadline specified in the contract. Providing responses timely is one of main strategy to mitigate claim [19, 20]. To keep this time-bar check, the provision should be fully acquainted by employees and their communication should be effective [21].

(4) Substantiation

The work elements for substantiation regards document substantiation from site and head office. It is necessary to make appropriate logic to get the indemnification through the raised claims [2, 22]. Most of the previous studies mentioned that major weakness of claim management work is the immature, insufficient evidence [23–25]. If an organization keeps records properly, it will have less difficulties in substantiating the cause and effect for claims.

In addition to this literature review, industry expert interviews have been conducted to supplement the detailed tasks of each category. 21 experts from nine construction companies and one construction claim consulting company were interviewed on the subject of claim management issues [26]. Based on the literature review and industry expert interviews, 20 work elements representing four work processes are identified.

As an example of survey design, the first two questions asked the updating and sharing of the claim log database within the company. Based on the literature review, it was found that operating database for claims is substantially important [17, 20]. This is specified by industry experts interviews who particularly highlighted the importance of utilizing log data within the company. Through this pre-

investigation regarding entitlement check work, the keyword has been investigated as claim log and that database, so the final question regarding this work has been set as “Claim logs of each case shall be properly updated and managed in accordance with the relevant provision”.

As another example, for the questions about the substantiation work function, Kartam (1999) emphasized the importance of daily inspection reports as a type of legal document reporting the facts on the jobsite [24]. Kim et al. (2004) stressed the importance of substantiation document management which includes client instruction management, record of site situation as daily construction reports, and meeting minutes [23]. In addition to this academic bases, the actual documentation systems that construction companies currently operate project have been investigated through the field consultation. According to this background, the detailed documentation work elements in this substantiation category have been designed. Overall, 20 questions representing four work functions were developed.

4. DATA COLLECTION AND RESULTS

The online survey was distributed to employees working at more than 10 general contractor companies in South Korea. 104 survey responses were collected from various construction companies. Among them, 10 survey data which have more than 60% of missing values were removed. After all, 94 data were included for the data analyses. Table 2 summarizes the database by industry sector and respondents' work experiences. As shown in the table, the plant industry submitted the highest number of data, data by industry sector were distributed relatively evenly. The average work experience was 18.9 years.

Table 2. Dataset by Industry Sector and Work Experience (n=94)

variable	category	N	%
Industry Sector	Building	23	24%
	Civil	23	24%
	Plant	39	41%
	Others	9	10%
	Total	94	100%
Work Experience	~10 yrs.	17	18%
	10~15 yrs.	25	27%
	15~20 yrs.	19	20%
	20~25 yrs.	11	12%
	25~30 yrs.	10	11%
	30yrs.~	12	13%
	Average	18.9	(years)

4.1. Status of claims management work

Table 3 presents the descriptive statistics for each work element and category. Because of the missing responses, the sample sizes being used for each work element vary from 79 to 94. A higher mean score means respondents more agree on the statement describing the work element. The category overall scores are calculated by averaging the element scores. When calculating the category overall scores, missing values were replaced by the mean values for each category of the respondent, which is a typical way to deal with missing data [27]. Replacing the missing values was applied only for the data that a respondent answered more than two-thirds of questions. The internal reliability for each category has been reported as Cronbach's alpha in Table 3. The category of Entitlement check, Potential event check and Task for Substantiation had a Cronbach alpha more than 0.7, which is considered relevant [28]. The time-bar check category had a Cronbach alpha of 0.682, which is questionable but near to acceptable range[29].

In terms of the category overall score, Task for Substantiation shows the highest mean score, 3.516, as shown in Table 3. The category also shows the lowest standard deviation ($SD=0.665$). In summary, the general contractors in South Korea consistently insist that tasks for substantiation have been maintained better than other major work functions for claim management. Documentation work has been frequently mentioned as the most critical element to success of construction claim [25]. As it has been regarded as one challenging task for claim management [24], it was expected that the mean score for this work function is low. One possible way to interpret this conflicting result may be the companies that respondents work. Those companies are major construction companies in South Korea. Thus the processes for documentation have been established relatively well. Future studies are necessary to investigate the relationship between company size and claim management process. Within the work function, the work element “items for weekly meetings and daily construction reports are recorded and shared” shows the highest mean score.

Table 3. Descriptive Statistics for Each Work Element and Category

Work Function	Question	N	Mean	Std.dev
Entitlement Check	1 The database of claim issues is maintained by and shared among claim managers and staff in relevant departments	79	2.330	1.900
	2 Claim logs of each case shall be properly updated and managed in accordance with the relevant provision.	84	2.740	1.743
	3 When a project is launched, the relevant department of the head office conducts a preliminary orientation regarding potential contract/claim risks.	92	3.580	1.131
	4 During the initial setting-up stage of a project, interpretation of the contract, determination of the situation at the site, and other relevant tasks are shared among all participants.	94	3.630	0.916
	5 After the launch of the project, participants smoothly coordinate claim-handling works according to their R&R.	94	3.390	0.870
	6 Those in charge check claim risk issues, which are expected to occur in each project execution stage on a regular basis.	94	3.540	1.002
Category Overall ($\alpha = 0.784$)			94	3.233
Potential Event Check	7 If a potential event occurs which could lead to a claim, it is directly shared by the staffs of the head office, who are in charge of claims, through a system or a relevant provision.	93	3.380	0.977
	8 When a potential event occurs which could lead to a claim, the information about it is immediately shared among the relevant staff.	94	3.360	0.926
	9 When such a potential event is shared, feedback of an expert or the dedicated team of the head office is immediately conveyed to the site.	94	3.450	0.946
	Category Overall ($\alpha = 0.800$)			94
Time-bar Check	10 A provision or a dedicated team has been well established to interpret and share any claim-related clauses (regarding the time bar for a claim event, etc.) of the project contract.	94	3.810	0.871
	11 All staff related to the project are well acquainted with claim-related clauses of the contract (with the help of preliminary orientation/regular training or workshop, etc.).	94	3.280	0.860
	12 The provision (specifying the list of main documents to be submitted, preparation of documents, and handling work for a claim received) is faithfully followed.	88	2.350	1.626
Category Overall ($\alpha = 0.682$)			94	3.170
Task for Substantiation	13 There is a provision regarding the dispatch of onsite experts (QS, Scheduler) or support for the relevant department by the head office during the claim process.	84	2.810	1.704
	14 During the documentation stage, feedbacks are communicated to relevant departments (contract team, legal affair team, etc.) to a reasonable level.	94	3.870	0.907

Work Function	Question	N	Mean	Std.dev
15	All the instructions given and agreements made orally by clients (or supervisors) during inspections or meetings are documented.	94	3.520	0.826
16	Items (including information about construction quantity and schedule) for weekly meetings and daily construction reports are recorded and shared.	94	3.900	0.749
17	work process regarding recording of situations at the site (labor attendance, equipment, construction details, etc.) is faithfully followed.	91	3.450	1.285
18	In case a claim-related issue occurs, staff are instructed to take photos and share them with the persons concerned. (e.g., excessive inspection of the client or the supervisor, demand of design modification for the site, accelerating, and other similar cases that may generate additional costs).	93	3.660	0.759
19	The latest schedule of the project is appropriately managed and shared in accordance with the relevant provision and system.	89	2.910	1.788
20	The schedule of the project is appropriately updated (weekly, monthly, etc.) according to the provision regarding phase updatation frequency.	93	3.880	0.720
Category Overall ($\alpha = 0.705$)		94	3.516	0.665

(Note: α denote Cronbach's Alpha)

Contrary to Task for Substantiation, the work function “Time-bar Check” shows the lowest mean value and the highest standard deviation. Particularly, the work element “The provision (specifying the list of main documents to be submitted, preparation of documents, and handling work for a claim received) is faithfully followed” shows the lowest mean value with the highest standard deviation. This result is probably related to the lack of training about claim regulations and sharing of contract interpretation. For better claim management, it may be necessary to establish a better process to train employees for claim regulations and share them effectively.

For the work element level, there are four work elements which have mean values lower than 2. These four elements, element numbers 1, 2, 12, and 13, are about sharing information about claim management with relevant employees. Considering the fact that these four elements have high standard deviation values, these probably are the key work elements differentiating companies maintaining better claim management processes in South Korea.

Overall, it was found that general contractors in South Korea are relatively good at tasks for substantiation and have more room for improvement for the works related to time-bar check. These strength and weakness show the same aspect in terms of deviation. This result shows that the industry experts think that updating the documents at project sites and head offices is processed well. However, they answered that these documents are not linked to real claims due to participants' lack of awareness about contracts and claims. Another possible interpretation is that the documents and data created are not properly used for claims because of the immaturity of the sharing system or work procedure. Therefore, in order to promote the claim management from the viewpoint of contractors, processes that help all relevant participants understand the status and condition of claims and share data required to address them properly should be established.

4.3. Difference between Industry sector

In order to investigate the difference in management status by industrial sector, this research divided the data into four groups as shown in Table 2. For the three industry sectors excluding “others” in Table 2, analysis of variance(ANOVA) test was carried out to check whether there is a statistically significant mean value differences for the claim management work functions by industry sector. Table 4 summarizes the results. As shown in the table, all of the work functions show the highest mean values in the plant sector. The building sector, on the other hand, shows the lowest mean values for Potential Event Check, Time-bar Check, and Task for Substantiation. For the ANOVA test, the significances for the four work functions are higher than the significant level of $\alpha = 0.05$. Thus it can be concluded that the claim management work function differences in terms of industry sector are not statistically significant at the level of $\alpha = 0.05$. Even though the result shows no statistically significant difference,

the plant sector tends to have higher mean values for all of the work functions. Plant projects tend to have much higher total project costs than projects in other sectors. Thus they tend to spend more management efforts than other industry sectors [14]. This is probably why the industry sector shows higher mean values. Further studies are recommended to investigate the claim management process by industry sector.

Table 4. Analysis of variance(ANOVA) by Industry Sector

Work Functions	Building			Civil			Plant			ANOVA	
	N	Mean	SD	N	Mean	SD	N	Mean	SD	Fvalue	Sig.
Entitlement Check	23	3.035	1.024	23	3.022	0.796	39	3.455	0.832	2.487	0.089
Potential Event Check	23	3.290	0.713	23	3.348	0.685	39	3.436	0.940	0.244	0.784
Time-bar Check	23	2.978	1.035	23	3.145	0.869	39	3.218	0.936	0.466	0.629
Task for Substantiation	23	3.481	0.694	23	3.490	0.625	39	3.566	0.706	0.149	0.862
Overall	23	3.242	0.739	23	3.276	0.537	39	3.460	0.727	0.923	0.401

5. CONCLUSION

This research investigates the current work process of general contractors in South Korea in terms of the claim management. A survey with 20 questions about the construction claim management process was developed based on the literature review and industry experts interviews. By using 94 data collected by the practitioners having experiences in the claim management, it was found that Task for Substantiation shows the highest mean value among the four work functions investigated in this study. On the other hand, it was also found that Time-bar Check shows the lowest mean value. Thus in order to improve the claim management process, rather than focusing on document preparation works, companies need to focus more on revising their processes such that employees understand the contract condition properly and share information properly when claims occur.

In addition, when comparing the claim management process by industry sector, it was found that the plant sector tends to show higher mean values for the four work functions of claim management but the differences among industry sectors are not statistically significant at the level of $\alpha = 0.05$. It was inferred that the differences among the industry sector are related to the characteristics of projects in each section but more studies are necessary to validate it.

The main contribution of this study is to diagnose the current practitioners' perception about claim management in South Korea. The results also should be helpful when practitioners establish plans to improve their claim management process which becomes more important nowadays.

This study is not free from limitations. The main limitation of this study is the data source. Based on the results of the questionnaire survey, this research examined the status of field claim management tasks from the perspective of general contractors. However, as all of the data were submitted by general contractors in South Korea, the findings should not be generalized. As companies in different countries may have difference claim management processes, future studies using the same survey for respondents from various countries are recommended to generalize the findings. In addition, the claim management processes can be influenced by company size. It is reasonable to assume that smaller companies may have different claim management processes because of their limited amount of resources. Data used in this study are from employees working in major construction companies in South Korea. Studying the claim management processes by company size can be another interesting topic to be investigated. As another topic of future study, the authors plan to investigate the relationship between process consistency measured by the dataset in this study and claim management performance [26]. It will be hypothesized that companies having more consistent claim management work process tend to show better claim management performance.

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Evaluating Construction Market of ASEAN Nations

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Abstract: This research evaluated the construction market and project environment of nine nations within the ASEAN members. Quantitative data from global consulting firms and international organizations were identified and normalized for evaluation. The result of the analysis was that Indonesia was ranked highest for construction market growth while Singapore was ranked highest for stability of project environment. The research results can be utilized by construction companies that are planning on entering the construction market within the ASEAN members.

Key Words: ASEAN, Construction Market, Evaluating

1. INTRODUCTION

Infrastructure demand of ASEAN members (2016~2030) is evaluated to be 3.147 trillion dollars. The scale of the construction market in the region is estimated to grow due to policies related to infrastructure improvement aimed to alleviate development gaps and enhance economic growth [1]. In addition, growing urbanization effect and intensified industrialization are drastically increasing the demand for various infrastructure facilities which has led to various global construction companies in entering the ASEAN market [2]. This research utilizes objective data of the ASEAN members in order to evaluate the construction market per nation and suggest basic information that can be utilized by construction companies that plan to enter the market.

2. SCOPE AND METHODOLOGY

This research analyzed data of nine nations excluding Brunei Darussalam from the ASEAN members that were provided by international organizations and consulting companies.

Acquired data had to be standardized with the following method as the units of the indexes differed for each evaluation criteria. Criteria where a higher value is better were normalized utilized Equation (1), and criteria where a lower value is better were normalized utilizing Equation (2). [3]

$$\text{Normalization process} = \frac{(X - \text{Min } X)}{(\text{Max } X - \text{Min } X)} \times 9 + 1 \quad (1)$$

$$\text{Normalization process} = \frac{(\text{Max } X - X)}{(\text{Max } X - \text{Min } X)} \times 9 + 1 \quad (2)$$

Two classifications, construction market growth and stability of project environment, were defined to evaluate the nations. Data for each evaluation criteria within the classifications were gathered from reports by consulting firms and international organizations. Details of the evaluation criteria are as shown in <Table 1>.

Table 1. Evaluation Criteria for ASEAN members

Classification	Evaluation Criteria	Code
Construction market growth	Construction industry value (billion, 2019 forecast)	A-1
	Construction Industry Value, Real Growth (2019 forecast)	A-2
	Construction Industry Value, % of GDP (2019 forecast)	A-3
	GDP (billion, 2019)	B-1
	GDP growth (%, 2019)	B-2
	Urban population (%, 2017)	B-3
	FDI Flow: Greenfield Project (million, 2018)	B-4
	Inflation (%, 2019)	C-1
	Sovereign credit ratings (2019)	C-2
Stability of project environment	Global terrorism index (2018)	C-3
	Corruption perception index (2018)	C-4
	Logistics Performance Index (2018)	D-1
	Dealing with construction permits (2018)	D-2
Project Environment	Enforcing contracts (2018)	D-3
	Paying taxes (2018)	D-4

In order to identify the weight for each evaluation criterion, Korean experts (3 academia persons, more than 5 years of project or research experience in South-East Asia) on overseas construction were surveyed. The weights of the evaluation criteria are as follows.

Table 2. Weights by each Evaluation Criteria

Evaluation Criteria	Code	Source	Weight
Construction market growth	A-1		40.0%
	A A-2	Business Monitor International [4]	35.0% 52.0%
	A-3		25.0%
	B-1	International Monetary Fund [5]	40.0%
	B B-2		10.0%
		Asian Development Bank [6,7]	48.0%
	B-3		25.0%
	B-4	United Nations Conference on Trade and Development [8]	25.0%
	C-1	Asian Development Bank [6]	25.0%
Stability of project environment	C C-2	Organization for Economic Cooperation and Development [9]	30.0%
	C-3	Institute for Economics & Peace [10]	15.0% 46.0%
	C-4	Transparency International [11]	30.0%
	D-1	Arvis et al. [12]	30.0%
D	D-2		30.0%
	D-3	World Bank [13]	25.0% 54.0%
	D-4		15.0%

3. ANALYSIS AND RESULTS

The analysis results of the construction market growth indexes are as follows. Among the three evaluation criteria of construction market status (A), Indonesia has the highest construction industry value (A-1) of \$128 billion, Myanmar had the highest construction industry value, real growth (A-2) of 14.67%, and Cambodia had the highest construction industry value, % of GDP (A-3) of 12.60%. Among the four evaluation criteria of economy and investment status (B), Indonesia has the highest GDP (B-1) of \$1,100.9 billion, Cambodia has the highest GDP growth (B-2) of 7.0%, Singapore had the highest urban population (B-3) of 100.0%, and Indonesia had the highest FDI Flow: Greenfield Project (B-4) of \$392 billion.

Table 3. Construction market growth Statistics Data

Criteria	Construction market status			Economy and investment status			
	A-1 (billion)	A-2 (%)	A-3 (%)	B-1 (billion)	B-2 (%)	B-3 (%)	B-4 (million)
Cambodia	3.36	11.35	12.60	26.98	7.0	23.0	3,056
Indonesia	128.04	7.03	10.60	1,100.91	5.2	54.7	39,238
Lao PDR	1.19	7.23	5.60	20.15	6.5	34.4	2,208
Malaysia	19.14	6.10	4.90	373.45	4.5	75.5	14,145
Myanmar	7.09	14.67	7.70	65.67	6.6	29.5	4,965
Philippines	29.69	10.39	7.70	356.68	6.4	46.7	22,548
Singapore	14.45	2.82	4.00	372.81	2.6	100.0	16,439
Thailand	13.57	5.03	2.60	516.66	3.9	49.2	7,273
Vietnam	15.93	7.23	5.80	260.30	6.8	35.0	29,147

The analysis results of the stability of project environment indexes are as follows. Among the four evaluation criteria of economy and social environment (C), Thailand had the lowest inflation (C-1) of 0.98%, and Singapore scored 0.00 on both sovereign credit ratings (C-2) and global terrorism index (C-3). In addition, Singapore was evaluated for corruption perception index (C-4) with a value of 85 points. Excluding inflation criteria, Singapore was evaluated to be the highest on the other three criteria compared to other nations.

Table 4. Stability of project environment Statistics Data

Criteria	Economy and Social Environment				Project Environment			
	C-1 (%)	C-2 (Index)	C-3 (Score)	C-4 (Score)	D-1 (Score)	D-2 (Score)	D-3 (Score)	D-4 (Score)
Cambodia	2.54	6.00	0.02	20	2.58	44.23	31.75	61.28
Indonesia	3.34	3.00	4.54	38	3.15	66.57	47.23	68.03
Lao PDR	3.10	7.00	1.68	29	2.70	67.94	41.99	54.22
Malaysia	2.00	2.00	2.70	47	3.22	86.96	68.23	76.06
Myanmar	7.52	6.00	5.92	29	2.30	70.35	24.53	63.94
Philippines	3.84	3.00	7.18	36	2.90	68.58	45.96	71.80
Singapore	1.33	0.00	0.00	85	4.00	84.73	84.53	91.58
Thailand	0.98	3.00	6.25	36	3.41	71.86	67.91	77.72
Vietnam	3.09	4.00	0.66	33	3.27	79.05	62.07	62.87

Equation (1) was utilized on the criteria of construction market growth which are shown below.

Table 5. Standardization Data for Construction market growth

Criteria	Construction market status			Economy and investment status			
	A-1	A-2	A-3	B-1	B-2	B-3	B-4
Cambodia	1.15	7.48	10.00	1.06	10.00	1.00	1.21
Indonesia	10.00	4.20	8.20	10.00	6.32	4.71	10.00
Lao PDR	1.00	4.35	3.70	1.00	8.98	2.33	1.00
Malaysia	2.27	3.49	3.07	3.94	4.89	7.14	3.90
Myanmar	1.42	10.00	5.59	1.38	9.18	1.76	1.67
Philippines	3.02	6.75	5.59	3.80	8.77	3.77	5.94
Singapore	1.94	1.00	2.26	3.94	1.00	10.00	4.46
Thailand	1.88	2.68	1.00	5.13	3.66	4.06	2.23
Vietnam	2.05	4.35	3.88	3.00	9.59	2.40	7.55

The result of applying Equation (1) and Equation (2) on stability of project environment are as follows. Criteria that utilized Equation (2), in which lower values are better, were applied to C-1, C-2, and C-3.

Table 6. Standardization Data for Stability of project environment

Criteria	Economy and Social Environment				Project Environment			
	C-1	C-2	C-3	C-4	D-1	D-2	D-3	D-4
Cambodia	7.85	2.29	9.98	1.00	2.49	1.00	2.08	2.70
Indonesia	6.75	6.14	4.31	3.49	5.51	5.71	4.41	4.33
Lao PDR	7.09	1.00	7.90	2.25	3.13	5.99	3.62	1.00
Malaysia	8.60	7.43	6.62	4.74	5.88	10.00	7.56	6.26
Myanmar	1.00	2.29	2.59	2.25	1.00	6.50	1.00	3.34
Philippines	6.07	6.14	1.00	3.22	4.18	6.13	4.21	5.24
Singapore	9.52	10.00	10.00	10.00	10.00	9.53	10.00	10.00
Thailand	10.00	6.14	2.16	3.22	6.88	6.82	7.51	6.66
Vietnam	7.10	4.86	9.17	2.80	6.16	8.33	6.63	3.08

Overall, Indonesia ranked highest for construction market growth with a value of 7.90, which was followed by Philippines (4.90) and Vietnam (3.95). For stability of project environment, Singapore has the highest value of 9.87 and was followed by Malaysia (7.22) and Thailand (6.36).

Table 7. Results of the Application of Weights by Construction market growth and Stability of project environment

Criteria	Construction market growth			Stability of project environment		
	Construction market status	Economy and investment status	Total	Economy and Social Environment	Project Environment	Total
	52.0%	48.0%		46.0%	54.0%	
Cambodia	5.58	1.97	3.85	4.45	1.97	3.11
Indonesia	7.52	8.31	7.90	5.22	5.11	5.16
Lao PDR	2.85	2.13	2.50	3.93	3.79	3.86
Malaysia	2.90	4.82	3.82	6.79	7.59	7.22
Myanmar	5.47	2.33	3.96	2.00	3.00	2.54
Philippines	4.97	4.83	4.90	4.48	4.93	4.72
Singapore	1.69	5.29	3.42	9.88	9.86	9.87

Thailand	1.94	3.99	2.92	5.63	6.99	6.36
Vietnam	3.31	4.65	3.95	5.45	6.47	6.00

Utilizing the overall analysis, the nine nations were plotted on a graph as follows. The average of the X axis (construction market growth) was 4.14 and Y axis (stability of project environment) was 5.43.

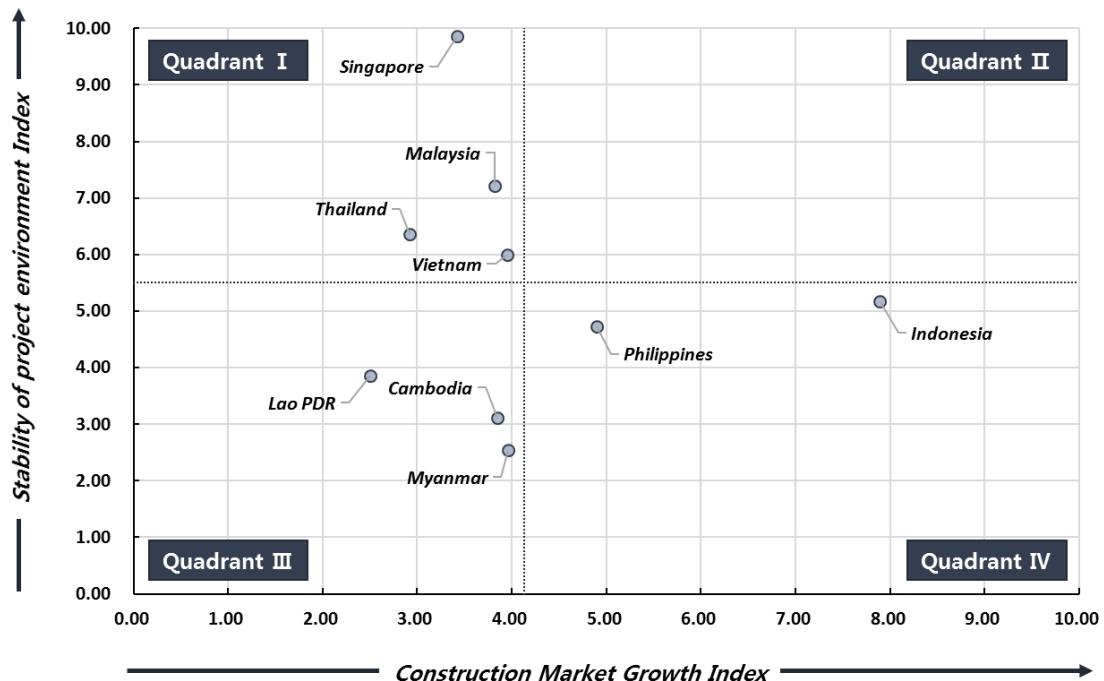


Figure 1. Graphic Representation of the Results on a quadrant matrix

According to the analysis result, Quadrant I, high stability of project environment yet low construction market growth, included Singapore, Malaysia, Thailand, and Vietnam. Quadrant II, high stability of project environment and high construction market grow, involved none of the ASEAN members. Quadrant III, which represents low stability of project environment and construction market growth, included Lao PDR, Cambodia and Myanmar. Finally, Quadrant IV, low stability of project environment but high construction market growth, included Indonesia and Philippines.

It is possible to suggest the following advice to construction companies that plan on entering the ASEAN member. For the four nations (Singapore, Malaysia, Thailand, and Vietnam) in Quadrant I, companies should prioritize in entering the above nations due to their high stability of the project environment. Especially, Singapore was ranked high on stability of project evaluation, which presents that it is one of the most stable markets among the ASEAN members. Singapore scored relatively high on political/economic stability compared to other nations. Singapore also has business-related policies and procedures, and infrastructure to support foreign investors in the nation. However, due to its high stability, it is likely that competition among construction companies are very intense. Observing where global construction companies (250 firms) are advancing, Singapore, Malaysia, Thailand, and Vietnam consisted of 51, 69, 50, and 54 foreign firms in the nation [14]. Therefore, it would be necessary to analyze the strengths and competitive advantages of one's firm and then identify entrance strategies into the nation.

Indonesia and Philippines that are located in Quadrant IV have high construction market growth,

resulting in increased opportunities for construction companies in winning contracts in the region. Companies need to identify methods to mitigate risks when entering these nations. In particular, companies need to consider identifying projects with high stability. Governments in both nations are implementing infrastructure investment policies, which in turn will increase project orders from the public. It is most likely that such projects will be government or Multilateral Development Bank funded. Hence it will be necessary to consider participating in such projects with priority.

In addition, the Global Infrastructure Hub [15] estimated Indonesia's investment needs to be \$5.5 billion in 2019. However, it is forecasted that a funding cap of \$0.2 billion as the current investment trend in infrastructure is estimated to reach \$5.3 billion. The current local government is pursuing Public-Private Partnership contracts for various infrastructure projects to ensure stable economic growth. However, as the government currently lacks the funds, the financial procurement of the infrastructure project is composed of more than half by private funds, creating a situation for private sector to actively participate in the related projects. Nevertheless, consideration of 'weak logistic environment, land acquisition and financial procurement issues, lack of infrastructure material supply', and other barriers will be necessary [16].

For the Philippines, Build Build Build policy is pursued by the local government which focuses on infrastructure development. The government aims to revitalize the economy and create jobs through the policy and is currently expanding its cause towards developing housing/office buildings. Hence, it is possible to expect that the local construction market size will further expand as well. However, limitations on foreign entities in acquiring local construction license, corruption of public servants and inefficiency in administration, high logistics cost, unstable policy, crimes, and other issues need to be considered when planning on entering the local construction market [17].

4. CONCLUSION

After analyzing the ASEAN member's construction market and project environment, each nation had distinctively different characteristics. Hence, construction companies that plan on entering the ASEAN market need to carefully consider the characteristics of the subject nation and develop a strategy accordingly. For nations that have relatively high project risks, companies need to establish risk mitigation strategies prior to advancing into the nation. One method to achieve it would be to establish a joint venture or consortium with companies that already have entered the market. On the other hand, when entering a nation with high project stability, it will be necessary to identify projects where the company can have a competitive advantage as competition in the local market is likely to be saturated and fierce among other construction firms.

This research analyzed the basic data of ASEAN members to identify methods to enter the local construction market. The followings are the limitations and future research.

It will be necessary to apply other various evaluation criteria for construction market growth and stability of project environment. This research suggested results based on quantitative values provided by consulting firms and international organizations for objectivity. In order to accurately represent the construction market growth and stability of project environment for each nation, it is necessary to consult with local construction related experts or experts who have experience in a local project and acquire various qualitative information. In addition, there needs to be more participants when calculating the weight of each criterion. This research utilized the analysis results and plotted them on a graph. Nations were evaluated only based on the characteristics of the quadrant. However, in the future research, it will be necessary to analyze each nation in depth.

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IX. BIM-ENABLED AEC APPLICATIONS

III (C3)

A Framework to Automate Reliability-based Structural Optimization based on Visual Programming and OpenSees

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Abstract: Reliability-based structural optimization usually requires designers or engineers model different designs manually, which is considered very time consuming and all possibilities cannot be fully explored. Otherwise, a lot of time are needed for designers or engineers to learn mathematical modeling and programming skills. Therefore, a framework that integrates generative design, structural simulation and reliability theory is proposed. With the proposed framework, various designs are generated based on a set of rules and parameters defined based on visual programming, and their structural performance are simulated by OpenSees. Then, reliability of each design is evaluated based on the simulation results, and an optimal design can be found. The proposed framework and prototype are tested in the optimization of a steel frame structure, and results illustrate that generative design based on visual programming is user friendly and different design possibilities can be explored in an efficient way. It is also reported that structural reliability can be assessed in an automatic way by integrating Dynamo and OpenSees. This research contributes to the body of knowledge by providing a novel framework for automatic reliability evaluation and structural optimization.

Key words: Reliability-based Structural Optimization, Visual Programming, Generative Design, OpenSees, Dynamo

1. INTRODUCTION

The main objective of structural design is create an engineering system with specific safety, functional, and performance requirements under conditions of uncertainty [1]. In deterministic design optimization, the uncertainties of the structural system (i.e. dimensions, models, materials, loads, etc.) are taken into account in a subjective and indirect way, by means of partial safety factors specified in design codes. As a consequence, deterministic optimal solutions may lead to reduced reliability levels [2]. Reliability Based Design Optimization (RBDO) has emerged as an alternative to properly model the safety-under-uncertainty aspect of the optimization problem [3].

Thus, probabilistic analyses are needed in the development of such reliability-based design of structures [4]. Since they provide consistent levels of safety over various types of structural components, the reliability-based structural design methods are more flexible and rational than their counterparts [5].

Such a design procedure takes into account more information than the deterministic methods in the design of ship structural components [2]. This information includes uncertainties in the strength of various ship structural elements, in loads, and modeling errors in analysis procedures [4].

Since decades ago, various methods were proposed, including first and second order reliability method [3], Monte Carlo simulation [6], etc. However, most of these efforts focus on theory, computational complexity and design optimization methods [3, 7, 8], few of them have considered how

to automate the approach and to improve the applicability of these methods. In other words, the process of reliability evaluation is time-consuming, tedious and not all the possibilities are explored most of the time.

Recently, together with building information modeling (BIM) which captures all the data of a building structure in a single model, generative design (GD) based on parametrization is proposed [9, 10]. Currently, GD utilizes visual programming (VP) language to provide direct and convenient way for parameter calculation and process automation [11]. Nowadays, VP tools like Rhinoceros 3d and Dynamo are widely used in different applications, and both of them are quite easy to learn.

To automate the optimization process of reliability-based design, this paper proposes an integrated approach based on visual programming and OpenSees. The approach consists 3 parts, namely, parametrization, simulation model generation and simulation, reliability evaluation, which are described in section 2. Then, demonstration of the proposed approach is implemented and discussed in section 3. Finally, feasibility and potential benefits of the approach is then concluded in section 4.

2. METHODOLOGY

To automatic the model generation, performance simulation, and reliability evaluation process of structure optimization, an integrated framework is proposed as Figure 1. Generally, the framework consists three parts: parameterization, OpenSees-based simulation, and reliability evaluation. The first part takes visual programming approach to represent structural design in an parametric way, which makes it possible to generate different models by changing parameters. While the middle part utilizes OpenSees as the underlying performance simulation module, and automatic simulation file generation and OpenSees invocation are implemented. Finally, post processing of the simulation results and automatic reliability calculation are provided in the last part, which could evaluate the reliability of a structure automatically. Details of each part are as follows.

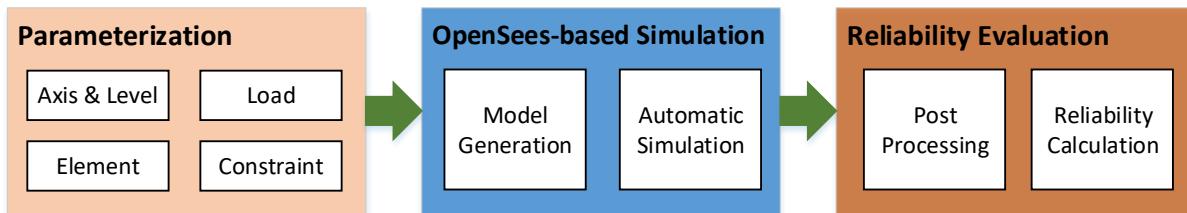


Figure 1. The proposed framework for automatic reliability-based structure optimization

2.1. Parameterization

Parameterization is a way that uses parametric equations to represent and generate design models. Generally, in a parametric model, a few parameters are selected and their relationships are carefully defined and created based on equations and programs, and all the properties of a design model can be derived from these parameters. That is, a design model is easily created by changing the pre-defined parameters, and the model generation and modification process can be taken as near real-time.

Therefore, this research adopts parameterization to automate the structural model generation process. As Shown in Figure 1, when creating a parametric structural model, four parts of information are considered, namely, axis and level, element, constraint and load. Parameters of the first 3 parts used for defining a parametric structural model are listed in Table 1. For axes and levels, count and offset/elevation are enough to create the axis grid and different levels. While, for a structural element, not only the category, material, section, but also the location is needed. And for the beam element, we use line as its location, while for the column element, point is used to express its location. In addition, modulus, weight per volume, etc. are defined to generate different materials.

Table 1. Parameters used for model generation

Group	Parameter	Data type
Axis	X offset, Y offset	float
Axis	X count, Y count	integer
Level	Elevation	float

Level	count	integer
Element	Category, Material	string
Element	Location	Point, Line
Element	Section	string
Element	Connection	string
Element	Constraint	string
Section	Size, Dimension	float
Material	Modulus, Weight per volume	float

After capturing all the needed parameters, their relationships are defined based on visual programming, or more concisely, Dynamo. Together Autodesk Revit, Building Information Modeling (BIM) –based structural model can be generated for further collaboration and manufacturing purpose.

For example, when offset and count of the axes are provided, a series of intersection points and the corresponding grid can be generated (Figure 2). Given that column and element in Revit and Dynamo are considered as *StructuralFraming* elements, once location point and location line are provided, it is possible to create column and beam element based on *StructuralFraming.ColumnByPoint* and *StructuralFraming.BeamByCurve* respectively.

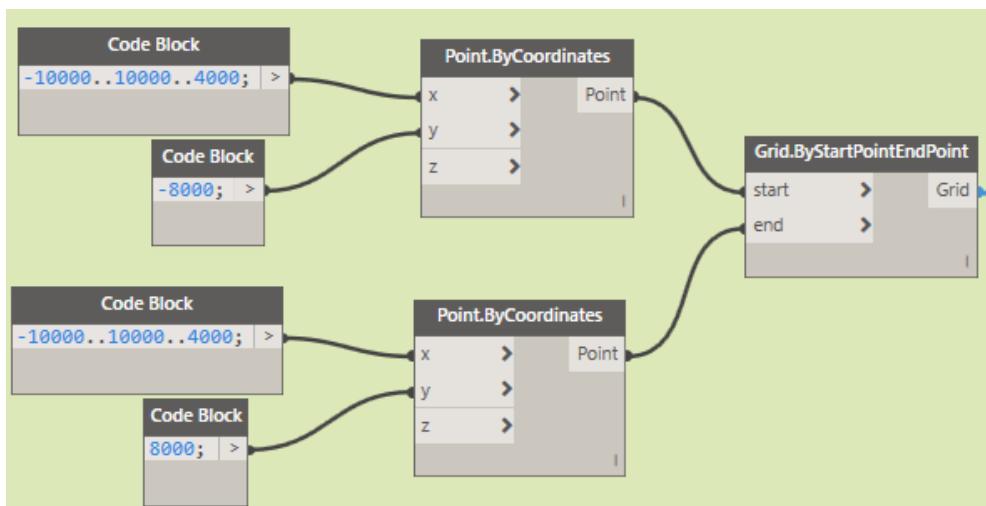


Figure 2. Generating grid based on parameters

In this way, when setting the X-direction count as 4, the Y-direction count as 2, the level count as 10, section of beams and columns as H type, a model as showed in the left part of Figure 3 is generated in seconds. Similarly, changing the X/Y-direction count and the level count, model like the right part of Figure 3 can be generated.

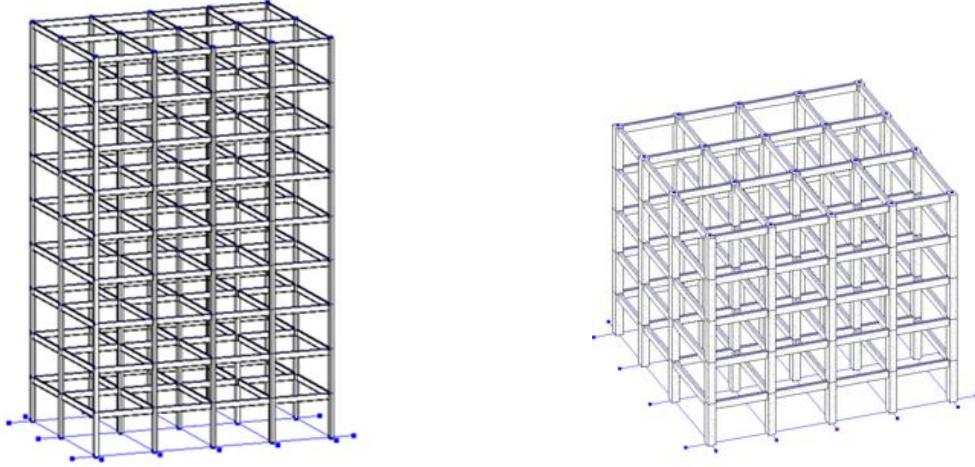


Figure 3. Generated models based on different parameters

Specially, when considering the reliability of a structure design, distribution of different loads should be taken account. In this paper, Monte Carlo simulation method is adopted. According to the design codes of China, extreme wind speed each year obeys the Gumbel distribution, and wind pressure obeys similar distribution. In literature [12], it is suggested that we can use the following function to represent the distribution of wind pressure in a 50-year period:

$$F_w(x) = \exp\left[-\exp\left(-\frac{x - 0.982W_{0k}}{0.158W_{0k}}\right)\right] \quad (1)$$

Where W_{0k} is the basic wind pressure defined in building code [13], and can be calculated using the following equation:

$$w_{0k} = \beta_z \mu_s \mu_z w_0 \quad (2)$$

While w_0 stands for the basic wind pressure, and μ_z , μ_s , β_z are the wind pressure height coefficient, shape factor of wind load, and wind vibration coefficient respectively.

Following the same way, distribution of live load of each level can be defined as:

$$F_{LT}(x) = \exp\left[-\exp\left(-\frac{x - 0.423L_k}{0.084L_k}\right)\right] \quad (3)$$

Where L_k is the standard live load defined in building code.

However, dead load of a structure obeys normal distribution, and is noted as:

$$N(1.06G_k, (0.074G_k)^2) \quad (4)$$

Where G_k is the standard dead load defined in building code.

Finally, based on the statistics collected from 45 cities and counties in China, it is suggested that the seismic action obeys Fréchet distribution, and in a 50-year period, distribution of the base shear force is defined as [14]:

$$F_Q(Q) = \exp\left[-\left(\frac{Q}{0.385Q_K}\right)^{-K}\right] \quad (5)$$

Where Q_K is the standard base shear force defined in building code, K is the location parameter of the distribution and is usually taken as 2.35.

For a random variable X , given its distribution function $F(X)$ and suppose u_i is uniformly distributed in the range of $(0,1)$, we can say that $x_i = F^{-1}(u_i)$ is a sample of $F(X)$. therefore, for the Gumbel distribution:

$$F(x_i) = \exp[-\exp(-\frac{x_i - \alpha}{\beta})] \quad (6)$$

The following can be derived:

$$x_i = \alpha - \beta \ln(-\ln u_i) \quad (7)$$

Therefore, according to the above-mentioned equations, the wind load and live load can be calculated and exported to the OpenSees file by custom defined Dynamo nodes based on some scripts (Figure 3). Then, using different coefficients, all the loads mentioned are combined together as a load combination applied to the structure. For a demonstration purpose, all coefficients are taken as 1.0 in this research.

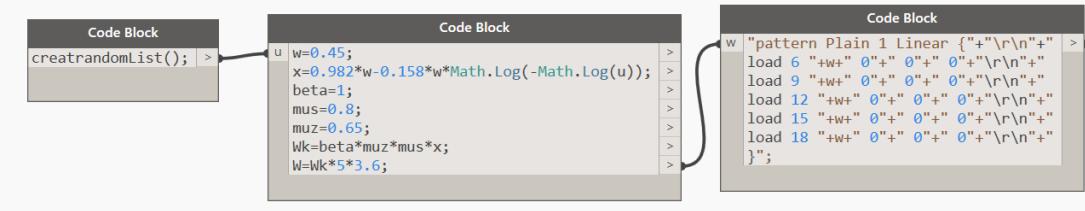


Figure 3. Generating load combination for structural simulation in OpenSees

2.2. OpenSees-based simulation

With the proposed parameterization method, structural design models can be generated automatically in an efficient way, and it saves quite a lot of time in design modeling. To further automate the performance simulation process, this section proposes an OpenSees-based simulation method.

Given that the OpenSees application is an open-source software, and adopts Tcl (tool command language) for data modeling and input, thus this research uses its Tcl specification to generate structural models as Tcl files for further simulation. Main definitions provided in OpenSees are listed in Table 2. Not only the dimension and degree of freedom, but also nodes, constraints, elements, and load can be defined in a Tcl file. Moreover, it is also possible to specify the output of the simulation.

Table 2. Data definition of OpenSees

Data type	Definition
model	model basic -ndm \$ndm -ndf \$ndf
node	node \$nodeTag (ndm \$coords)
constraint	fix \$nodeTag (ndf \$constrValues)
transformation	geomTransf Linear \$transfTag
frame element	element elasticBeamColumn \$eleTag \$iNode \$jNode \$A \$E \$Iz \$transfTag
load pattern	pattern Plain \$patternTag \$tsTag{}
uniform load	eleLoad -ele \$eleTag1 -type -beamUniform \$Wy
point load	load \$nodeTag (ndf \$LoadValues)

Since all the data needed in a Tcl file are already defined or generated based on the parameters and corresponding functions and equations, it is quite straightforward to extract relevant information and generate a Tcl file based on customized Dynamo nodes and scripts. Figure 4 shows an example of generated Tcl file.

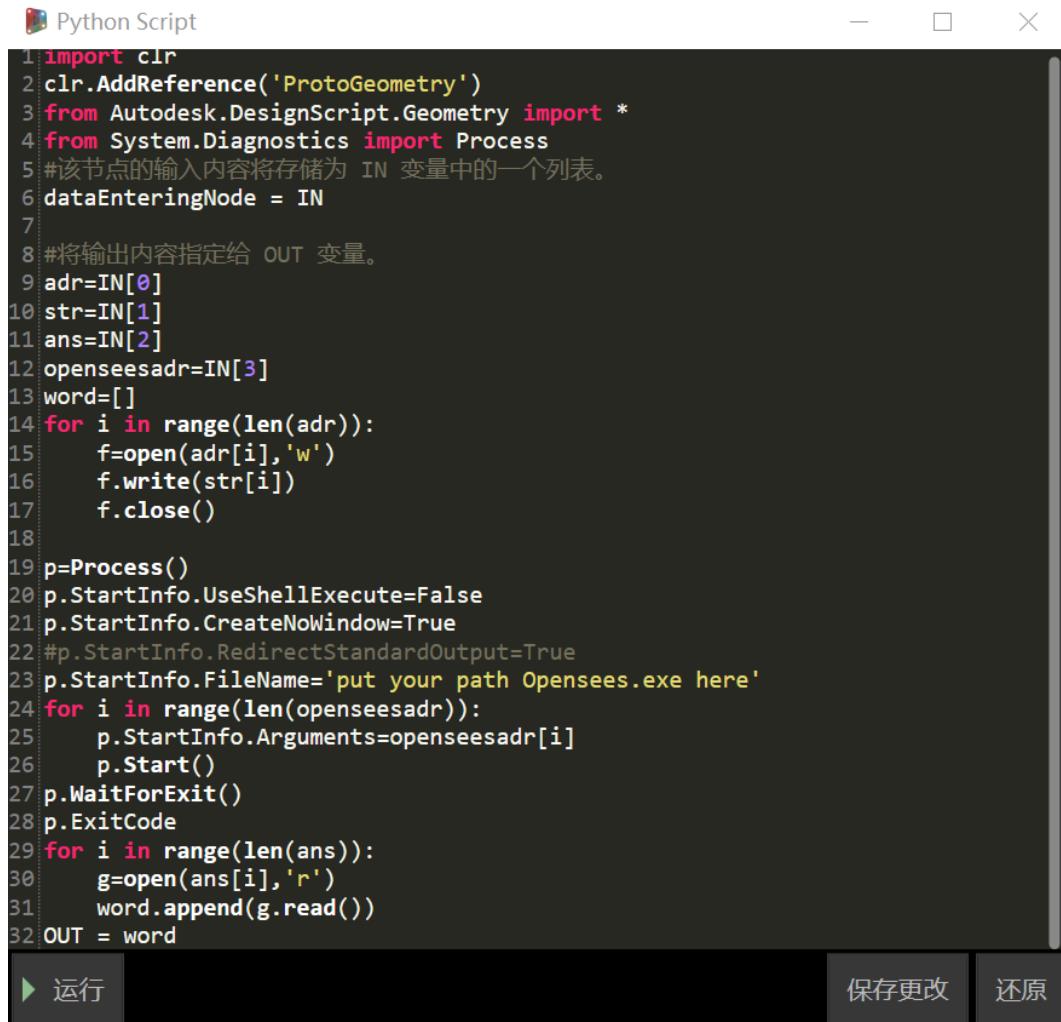
```

wipe
puts "System"
model basic -ndm 2 -ndf 3
puts "restraint"
node 1 6400.000000 0.000000
node 2 0.000000 0.000000
...
fix 1 1 1 1
...
puts "transformation"
geomTransf Linear 1
element elasticBeamColumn 1 1 4 17044.000000 206000 395061761.333333 1
element elasticBeamColumn 2 2 5 16440.000000 206000 495553000.000000 1
...

```

Figure 4. An exemplary Tcl file generated

What's more, since OpenSees is usually delivered as a command line application, it is possible to invoke the application based on command line commands. Therefore, according to the command line guide of OpenSees, this research created a Dynamo node based on some python scripts (Figure 5). With this Dynamo node, paths of generated Tcl files, configuration for performance simulation can be passed to OpenSees by command line, and the simulation can be started automatically in Dynamo. Thus, it is possible to generate required Tcl files and run the performance simulation in a fully automatic way, and manual working efforts of engineers are eliminated.



```

Python Script
1 import clr
2 clr.AddReference('ProtoGeometry')
3 from Autodesk.DesignScript.Geometry import *
4 from System.Diagnostics import Process
5 #该节点的输入内容将存储为 IN 变量中的一个列表。
6 dataEnteringNode = IN
7
8 #将输出内容指定给 OUT 变量。
9 adr=IN[0]
10 str=IN[1]
11 ans=IN[2]
12 openseesadr=IN[3]
13 word=[]
14 for i in range(len(adr)):
15     f=open(adr[i],'w')
16     f.write(str[i])
17     f.close()
18
19 p=Process()
20 p.StartInfo.UseShellExecute=False
21 p.StartInfo.CreateNoWindow=True
22 #p.StartInfo.RedirectStandardOutput=True
23 p.StartInfo.FileName='put your path Opensees.exe here'
24 for i in range(len(openseesadr)):
25     p.StartInfo.Arguments=openseesadr[i]
26     p.Start()
27 p.WaitForExit()
28 p.ExitCode
29 for i in range(len(ans)):
30     g=open(ans[i],'r')
31     word.append(g.read())
32 OUT = word

```

The screenshot shows a Python Script window with the title 'Python Script'. The code is a script that generates a Tcl file from input parameters and runs it using the OpenSees executable. The window has standard operating system controls at the top right. At the bottom, there are three buttons: '运行' (Run), '保存更改' (Save Changes), and '还原' (Reset).

Figure 5. Python script for invoking OpenSees in Dynamo

2.3. Reliability evaluation

According to the reliability theory, different variables can be chosen to reflect the function of a structure. And if the function of a structure is influenced by variables X_i ($i = 1, 2, \dots, n$), then the function of the structure can be defined as:

$$Z = g(X_1, X_2, \dots, X_n) \quad (8)$$

While $Z > 0$ means the structure can provide its function in a reliable way. When $Z < 0$, the structure loses its function or fails, and $Z=0$ is a transfer state between the two. Then the probability of $Z < 0$ is defined as the failure probability of a structure, and is denoted as P_f . Similarly, P_r is the probability of $Z > 0$, which is called the reliability of a structure. Obviously, the sum of P_f and P_r always equals 1. Generally, the function of a structure's bearing capacity is defined as:

$$Z = g(R, S) = R - S \quad (9)$$

Where R is the structure resistance, S is the load effect, and they obey the normal distribution $N(\mu_R, \sigma_R)$ and $N(\mu_S, \sigma_S)$ respectively. So we have $\mu_Z = \mu_R - \mu_S$, $\sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2}$, and then the reliability of structure failure can be derived:

$$P_f = 1 - P_r = 1 - p(Z < 0) = 1 - \int_{-\infty}^0 f_Z(Z) dZ = 1 - \Phi\left(-\frac{\mu_Z}{\sigma_Z}\right) = \Phi\left(\frac{\mu_Z}{\sigma_Z}\right) \quad (10)$$

Most of the time, we just use $\beta = \frac{\mu_Z}{\sigma_Z}$ as the indicator of reliability of a structure.

If taken displacement as the criterion for structural failure, maximum lateral displacement (MXD) of the structure is usually considered an appropriate indicator of structural performance according the building code. Thus, collected MXD of all the samples from output generated by OpenSees, average μ and standard deviation σ can be obtained. Therefore, let w denotes the maximum allowable lateral displacement, the reliability of the structure is then calculated as:

$$\beta = \frac{w - \mu}{\sigma} \quad (11)$$

Converting the above equations into customized Dynamo nodes, and together with Dynamo nodes for data extraction, the reliability of a structure is automatically calculated (Figure 6).

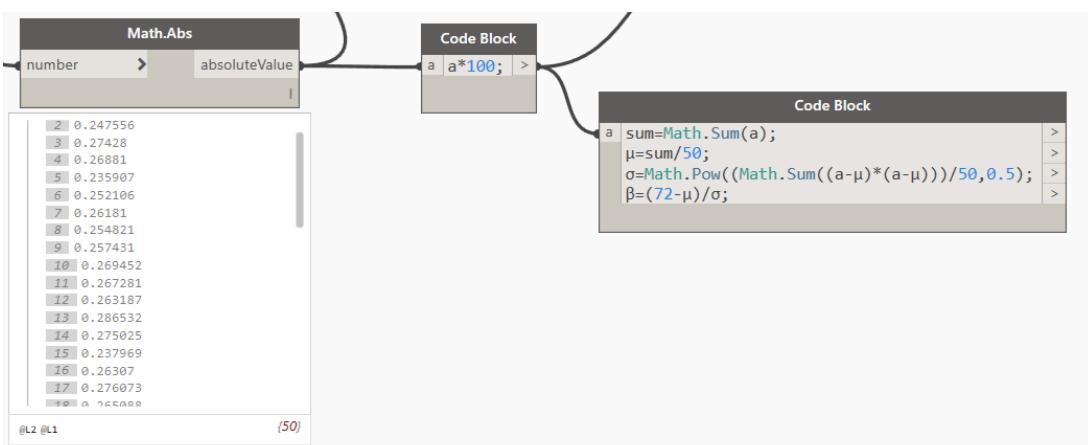


Figure 6. Customized Dynamo node for calculating reliability of a structure

3. DEMONSTRATION

Based on the above-proposed approach, automated structural model generation, simulation and reliability evaluation can be achieved. To further demonstrate and validate the feasibility and flexibility of the proposed approach, a five-story steel frame structure is used. Y-direction offsets of the frame are 6.4m and 7.7m respectively, while X-direction offset is 5m, height of each story is 3.6m, and total height of the frame is 18m (left of Figure 7). As listed at the right of Figure 7, sections of all the columns and beams are H sections, and their material is Q345B. When generating the load samples, 50-year design period is considered. Given that the shape is simple and the height of the structure is lower than 30m, wind vibration effect can be omitted, thus μ_s , β_z are both taken as 1.0 and μ_z is taken as 0.65. In addition, only elastic simulation is conducted for simplification.

When doing the optimization, total weight of the structure is taken as the objective function as an example, and only sections of columns and beams are changeable.

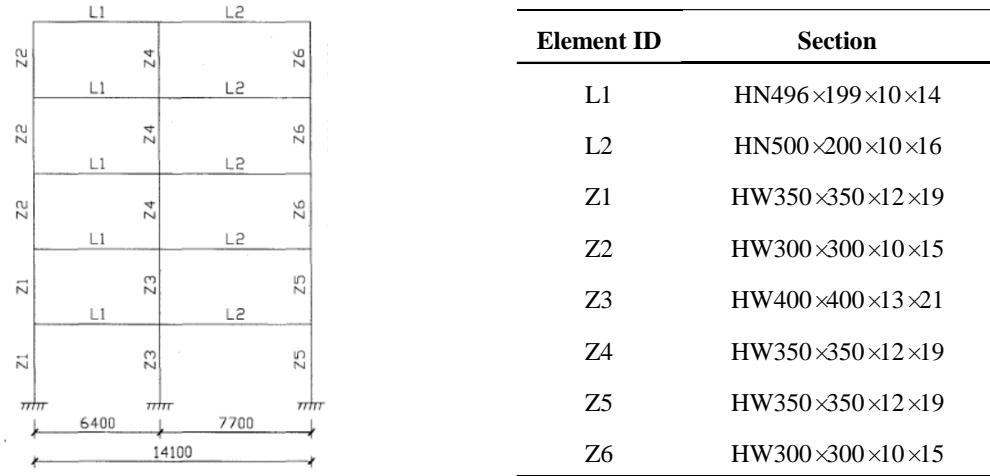


Figure 7. Parameters of the test case

Following the proposed parametric modeling approach, similar model like Figure 3 is created, and different load samples are generated based on their distribution (Figure 8).

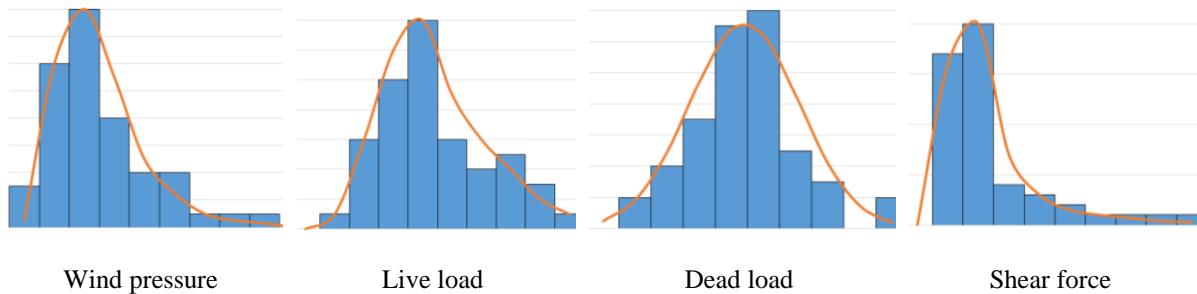


Figure 8. Generated load distributions

Then, following the proposed approach, structural performance is automated simulated and reliability of the structure can be calculated. Meanwhile, total weight of the structure is calculated at the same time. Therefore, the designer can see how the reliability and total weight change when different sections of structural elements are chosen (Figure 9). Finally, the designer can select appropriate section combinations considering the reliability requirements and the cost constraints (based on total weight).

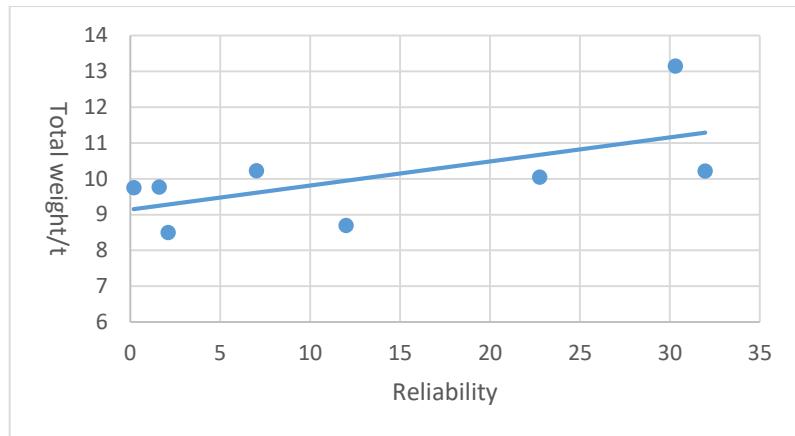


Figure 9. Reliability and total weight of different section combinations

Since Dynamo embeds complex programming codes and scripts as visual nodes, it is intuitive and easy to understand for non-experts. If an engineer or designer could understand the input and output of a Dynamo node, he or she can use just drag the node into work space and connect it with other nodes to create a computing process. Meanwhile, since Dynamo is also integrated with Autodesk Revit, it is possible to generate BIM models and share them with other stakeholders, thus improving the value of the generated models.

4. CONCLUSION

Reliability-based structural optimization is a well-known method for structural design. However, due to the complexity of structure, reliability is usually hard and time-consuming to calculate and approximate methods are always used. This research proposes a visual programming and OpenSees based approach to automate the model generation, simulation, and reliability evaluation process, therefore making it possible to get the reliability of a structure in a more time efficient way. Demonstration with a steel frame structural model shows that the proposed method is feasible and has the potential to automate performance-based reliability evaluation. Moreover, since the proposed method is implemented in Dynamo, it is also possible to generate BIM models for collaboration purpose. However, this research is still proof of concept, more improvements and extensions are needed in the future for complex structures and practical applications.

ACKNOWLEDGEMENTS

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X. RISK AND SAFETY MANAGEMENT IN CONSTRUCTION III (D1)

Measurement of Individuals' Emotional Stress Responses to Construction Noise through Analysis of Human Brain Waves

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Abstract: Construction noise is among the most critical stressors that adversely affect the quality of life of the people residing near construction sites. Many countries strictly regulate construction noise based on sound pressure levels, as well as timeslots and type of construction equipment. However, individuals react differently to noise, and their tolerance to noise levels varies, which should be considered when regulating construction noise. Although studies have attempted to analyze individuals' stress responses to construction noise, the lack of quantitative methods to measure stress has limited our understanding of individuals' stress responses to noise. Therefore, the authors proposed a quantitative stress measurement framework with a wearable electroencephalogram (EEG) sensor to decipher human brain wave patterns caused by diverse construction stressors (e.g., worksite hazards). This present study extends this framework to investigate the feasibility of using the wearable EEG sensor to measure individuals' emotional stress responses to construction noise in a laboratory setting. EEG data were collected from three subjects exposed to different construction noises (e.g., tonal vs. impulsive noises, different sound pressure levels) recorded at real construction sites. Simultaneously, the subjects' perceived stress levels against these noises were measured. The results indicate that the wearable EEG sensor can help understand diverse individuals' stress responses to nearby construction noises. This research provides a more quantitative means for measuring the impact of the noise generated at a construction site on neighboring communities, which can help frame more reasonable construction noise regulations that consider various types of residents in urban areas.

Keywords: Construction Noise, Stress, Electroencephalogram (EEG), Brain waves

1. INTRODUCTION

Noise, which is defined as any type of unwanted and unpleasant sound, is one of the most critical stressors that adversely affect urban residents' physiological and psychological health, as well as their quality of life [1]. Especially, significant numbers of people residing near urban construction sites suffer from noise pollution produced by various sources during construction work, including equipment, machinery, tools, and traffic [2, 3]. Considering that high-frequency, high-intensity, and impulsive patterns, which are common in construction noise [1, 4], are the key physical characteristics of noise pollution, the noise pollution caused by construction sites should be well-managed in urban areas to mitigate its adverse effects on urban populations.

Therefore, many countries strictly regulate noise pollution based on the sound pressure level, which is commonly expressed as a weighted decibel (dBA), in addition to the time and duration of noise emission, source of noise (e.g., construction equipment types), and nature and characteristics of the locality (e.g., residential area). For example, according to the noise regulation guidelines provided by the International Organization for Standardization, in industrial areas, noise levels in the daytime and nighttime should be lower than 70 dBA and 60 dBA, respectively [5]. Stricter guidelines are applied to urban residential areas (e.g., lower than 45 dBA in the daytime and lower than 35 dBA in the nighttime). However, it has been found that individuals react differently to noises and have different levels of tolerance to noise. As such, the noise sensitivity of any individual affected by noise should be considered in formulating construction noise regulations. In this regard, many studies have attempted to analyze individually varying psychological responses (e.g., annoyance, stress) toward noise based on subjective ratings such as the Weinstein noise sensitivity index [6], and socio-acoustic surveys [7]. However, such self-assessments can include possible biases caused by the subjective rating scales. In addition, because of the time and effort required to gather survey ratings, it is difficult to apply the method on an ongoing basis to diverse sources of noise in different scenarios. The lack of quantitative methods to measure stress makes it difficult to fully understand individuals' stress responses to noise. In this regard, the authors had proposed a framework to quantitatively measure emotional stress by using a wearable electroencephalogram (EEG) sensor that can decipher the human brain wave patterns caused by diverse stressors at construction sites (e.g., worksite hazards) [8]. In this previous study, the authors measured two important emotional dimensions, namely, a valence dimension from displeasure to pleasure and an arousal dimension from not aroused to excited. Because negative emotions contribute critically to human stress and the valence dimension of emotion is closely associated with unpleasant feelings and the consequent annoyance and stress [9], the authors' previous framework can be useful for quantitatively measuring individuals' stress responses to construction noise. In the present study, the aforementioned framework is extended to investigate the feasibility of using the wearable EEG sensor to measure individuals' emotional stress responses to construction noises in the laboratory environment, where subjects are exposed to various construction noises recorded at real construction sites.

2. STRESS MEASUREMENT

2.1. Impact of Construction Noise

In the literature, it has been claimed that construction noise has many negative effects on urban residents, including emotional stress, annoyance, and distraction, which adversely affect the physical and emotional well-being of individuals [1]. More specifically, a high noise level is directly associated with individual annoyance accompanied by displeasure and emotional upset [10]. Moreover, high noise levels lead to heightened arousal, thereby affecting human attention and hindering sleep and relaxation [11, 12]. To sum up, the abovementioned effects of noise can be explained based on two important dimensions of emotions, valence and arousal. The valence dimension explains feelings of pleasure or displeasure (e.g., annoyance due to displeasure), while the arousal dimension explains relaxed and aroused states [13, 14]. These emotional valence and arousal dimensions can be employed as representative features to measure and classify stress levels, even though stress is a very complex psychological state [9, 15]. In this regard, in a previous work, the authors of this study demonstrated a feasible means to measure the emotional valence and arousal dimensions through an analysis of human brain waves related to emotional stress by collecting EEG signals with a wearable EEG sensor [8]. This measurement method that directly captures brain activity is expected to facilitate more reliable and continuous measurement of different individuals' emotional stress responses to construction noise, which can contribute to a more in-depth understanding of the effects of construction noise on urban residents. To this end, the feasibility of the EEG-based measurement of emotional stress responses to construction noise should be tested further, which is the main objective of the present study. The measurement method developed by Hwang et al. [8], is explained in the following section.

2.2. EEG-based Emotional Stress Measurement

Figure 1 shows the framework of EEG-based emotional stress measurement method proposed by Hwang et al. [8]. Because EEG signals are highly vulnerable to signal artifacts, the removal of such artifacts is a very important step in this study. The major objective of [8] was to measure construction

workers' emotions by using wearable EEG sensors as they were working in the field, a scenario in which EEG signals are prone to considerably more signal artifacts. Before the research of [8], a framework for the removal of field EEG signal artifacts was proposed and successfully tested [16]. In the abovementioned study, EEG signals from 14 channels were collected and bandpass filters and notch filters were employed to remove significant extrinsic artifacts generated by external signal noise sources, such as electrode popping, movement artifacts, and wiring noise in the EEG sensor [8, 16]. Then, intrinsic artifacts such as signal noises due to blinking and movement of the eyes and movement of facial muscles were corrected by conducting an independent component analysis [8, 16].

After removal of the signal artifacts, power spectrum features (e.g., power spectral density: PSD) of the EEG signals were used to calculate the valence and arousal levels. A positive valence level (+) indicates a pleasant emotional state, while a negative valence level (-) indicates an unpleasant state. A positive arousal level (+) indicates an excited state, while a negative arousal level (-) indicates a relaxed state. This calculation was based on the PSD of the alpha and beta frequencies of the frontal lobe of the brain because the frontal lobe is associated with emotional control [8]. Based on this calculation, individuals' valence and arousal levels toward stressors, such as construction noise, can be determined.

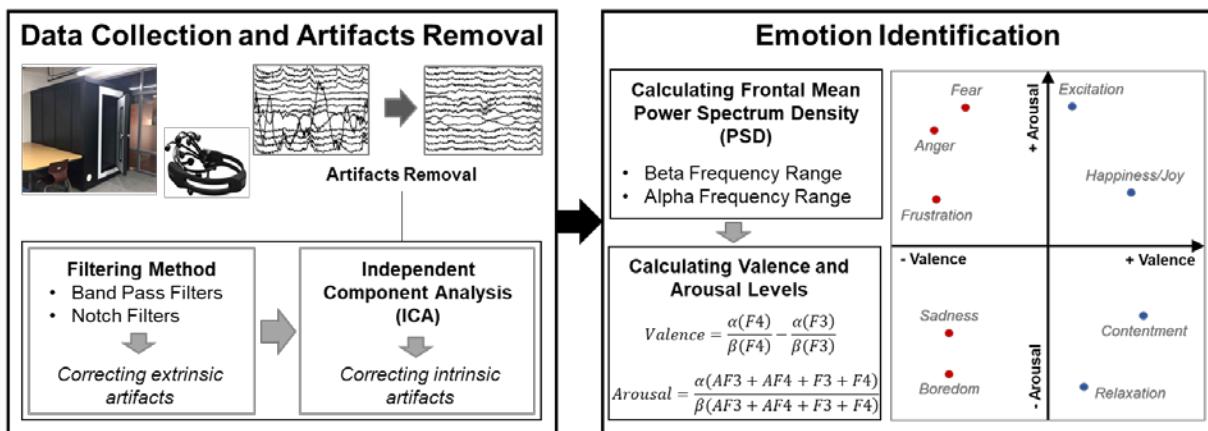


Figure 1. Framework of EEG-based emotional stress measurement

3. EXPERIMENTAL DESIGN

To investigate the feasibility of the EEG-based measurement of individuals' emotional stress responses to construction noise, we conducted a laboratory experiment. To generate construction noise stressors, the sounds made by construction equipment were recorded at a real construction site in which foundation work was in progress. Two different types of noise, namely, tonal and impulsive, were recorded from an earth auger and a pile driver, respectively. The noise of an earth auger is generally tonal while that of a pile driver is highly impulsive [5]. To produce various sound pressure levels, the recorded noises were adjusted to 40 dBA, 50 dBA, 60 dBA, 70 dBA, and 80 dBA.

In this experiment, three healthy subjects were recruited and exposed to a combination of two different construction noise types (i.e., steady and impulsive) at five sound pressure levels (i.e., 40 dBA, 50 dBA, 60 dBA, 70 dBA, and 80 dBA) inside an experimental auditory room over 10 sessions. During all sessions, subjects' EEG data were collected from the 14 channels of the wearable EEG sensor; each channel was operated at a sampling rate of 128 Hz. Each session lasted at least 5 min (i.e., more than 0.5 million data points in each session from 14 channels at the sampling rate of 128 Hz), and the subjects were allowed breaks of at least 10 min between sessions. The order of sessions was assigned randomly to minimize the order effect.

Because an individual's noise sensitivity can affect their emotional stress response [6], the subjects' noise sensitivities were measured using the 11-point personal noise sensitivity scale (from 0 to 10 points) before starting the experiment. In addition, the subjective level of emotional displeasure and annoyance toward each type of noise were surveyed using the 11-point annoyance scale (from 0 to 10 points) immediately after each session [7]. These subjective survey ratings were gathered to compare the subjects' emotional stress responses (i.e., valence and arousal levels) measured using the EEG signals

with the subjects' perceived feelings of stress. Details of the subjects and the experimental protocol are summarized in Table 1.

Table 1. Subject information and experiment protocol

Subject Information				Experiment Protocol					
No.	Age	Gender	Noise Sensitivity [0–10]	dBA	40	50	60	70	80
				Noise Type					
1	25	Male	6	Tonal (Earth auger)	E40	E50	E60	E70	E80
2	23	Female	8	Impulsive (Pile driver)	P40	P50	P60	P70	P80
3	24	Male	5						

4. RESULTS AND ANALYSIS

Figure 2 shows all subjects' emotional stress responses in terms of the bipolar dimensions of valence and arousal levels based on their EEG signals. In this figure, the triangular labels indicate the subjects' responses to tonal construction sounds (i.e., sounds from an earth auger), while the circular labels indicate the subjects' responses to impulsive sounds (i.e., sounds from a pile driver). The darker labels indicate subjects' responses to higher sound pressure levels. The table inside Figure 2 describes the subjects' perceived annoyance (on a scale of 0 to 10) due to diverse noise stressors.

As can be seen in this figure, all subjects have lower valence levels (i.e., more negative valence levels and more unpleasant emotional states) when exposed to any type of construction noise stressors compared to those in normal settings ("X" labels in Figure 2) devoid of significant noise stressors. In addition, the subjects exhibit lower (more negative) valence levels and are consequently more likely to have considerable emotional stress in general in environments with loud noises at high sound pressure levels (dBA). Meanwhile, the perceived annoyance survey results given in the table in Figure 2 indicate the subjects' tendency of high annoyance scale scores in environments with loud noises.

In addition, the subjects tended to have higher negative valence levels (i.e., more unpleasant emotions) under impulsive sounds compared to those under tonal sounds. The literature contains ample evidence supporting higher levels of personal annoyance under impulsive sounds owing to the highly fluctuating parameters of such sounds, which is consistent with the results obtained in the present study [7].

To summarize, significant changes in valence levels with sound pressure levels and noise types (i.e., tonal vs. impulsive) show the potential of the EEG-based method to measure individuals' emotional responses to noise stressors. Hwang et al. [8] demonstrated a significant correlation between negative valence levels and individuals' stress responses. Moreover, the annoyance scale, which is widely used to measure the effects of noise stressors on individuals' perceived feelings, is closely associated with feelings of displeasure and negative valence levels. Regardless of arousal levels, negative valence levels are linked to negative emotions, such as fear, anger, frustration, sadness, which affect individuals' stress levels. Therefore, valence level measurement can potentially be used to quantify urban residents' emotional stress responses to construction noise stressors.

Between the two dimensions of emotions, however, it is difficult to infer the impact of different noise stressors on subjects' arousal levels because of the possible effects of many uncontrollable factors on an individual's arousal levels (e.g., cognitive loads and distracting thoughts) and the small number of datasets. After confirming the results with a greater number of subjects, it is expected that the results of this study can be applied to devise more feasible construction noise regulations by considering the diverse features of noise sources and the stress responses of people residing in urban areas.

Notably, subject #2, who had the highest noise sensitivity levels, consistently showed negative valence levels with slightly positive arousal levels, even when exposed to low sound pressure levels. Although it is difficult to fully confirm the relationship between personal noise sensitivity and the EEG-based stress responses of the subjects in this study owing to the small sample size, the different emotional stress responses of individuals to construction noise imply that the differences should be considered when framing noise regulations to improve the quality of life of urban residents.

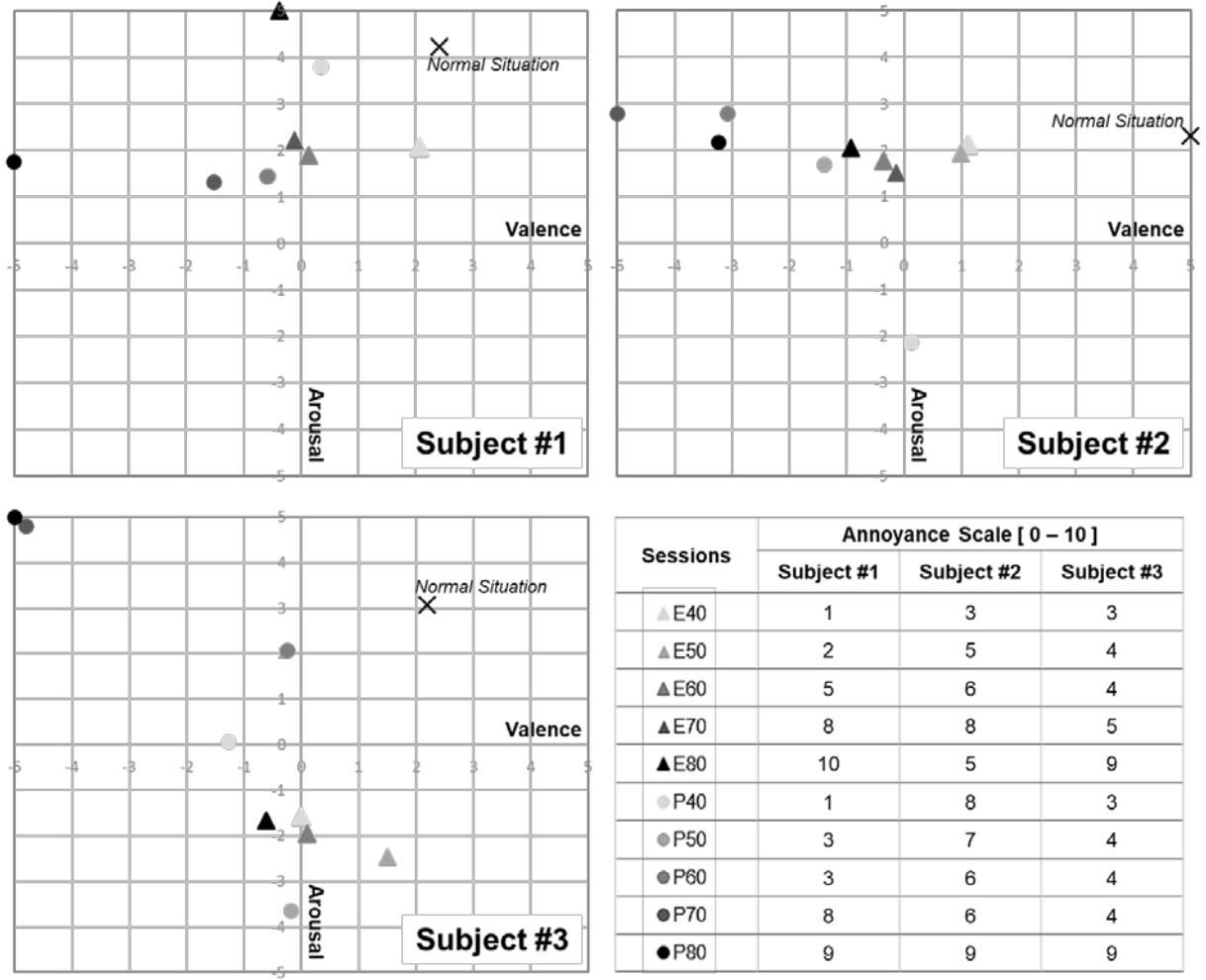


Figure 2. EEG-based emotional stress and perceived annoyance toward construction noises

5. CONCLUSIONS AND FUTURE WORKS

In this study, the feasibility of EEG-based measurement of individuals' emotional stress responses to construction noises was examined by applying a framework for quantitative emotional stress measurement proposed by the authors in a previous study. The results show that an individual's valence levels measured with the wearable EEG sensor are closely associated with noise types and sound pressure levels, as well as the individual's perceived feeling of annoyance, which indicates the potential of using the wearable EEG sensor for determining diverse individuals' stress responses to noise from nearby construction sites. This research can contribute to providing a more quantitative means to measure the impact of construction noise on communities in the neighborhood. The outcomes of this research are expected to help devise more feasible construction noise regulations by considering various types of residents with different noise sensitivities in urban areas, as well as various noise sources in construction sites. Future research will further validate the EEG-based measurement of individuals' emotional stress responses to noise through additional laboratory and real-world experiments with larger numbers of subjects. Further measurement and validation are expected to provide an in-depth understanding of the impact of construction noise on diverse urban residents (e.g., people of different ages, different physical and psychological statuses) in different scenarios.

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Proliferation of Health and Safety Documentation in Construction?

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Abstract: In addition to a range of H&S documentation, a range of actions, beliefs, interventions, practices, and states are important in terms of achieving optimum construction H&S. Conclusions include that H&S documentation facilitates and assists planning, organising, leading, controlling, and coordinating H&S. Furthermore, current H&S documentation: is inappropriate in that it can be complex, generic, lengthy, onerous, repetitive (duplicative), and vague; engenders dubious practices; generally, ‘does not add the potential value’; shifts the focus from the physical process, and could be improved. Recommendations include: industry associations should review their ‘audit system’ to interrogate the allocation of points; H&S documents must reflect the intention of the requirement; the synergy between H&S documentation, and actions, interventions, and practices should be investigated, digested, and focused upon, and ‘audits’, or rather inspections, should focus more on the physical process, actions, interventions, and practices, than documentation.

Key words: construction, documentation, health and safety

1. INTRODUCTION

The Master Builders South Africa (MBSA) has a national H&S Audit System, which is used to assess contractors in terms of H&S performance, either during initial, general, H&S star grading, or H&S competition assessments. A study conducted by Smallwood (2015) investigated where the focus of such an H&S Audit System should be, the reason being that although audits focus on the physical aspects of construction, there was concern that there was too much focus on administration. Furthermore, at the time, anecdotal evidence, the findings of audits, and various research studies indicated that there should be more focus on risk management and hazard identification and risk assessment. Findings of the study include that although all eleven aspects of an H&S programme as posed to the respondents are important in terms of achieving optimum H&S in respondents’ organisations, the joint-first ranking of hazard identification and risk assessment (HIRA), and risk management, led to the conclusion that these are critical, and that emphasis should be placed on these aspects during auditing. Then, although administration and legal requirements was ranked third, and was marginally more important than the physical aspects, there was a high level of agreement with ‘The emphasis in terms of H&S should be on the physical aspects’. The relatively high agreement with ‘Too much administration results in ticking boxes and cutting and pasting’, ‘Too much administration is required relative to H&S to the detriment of the physical aspects of H&S’, and ‘Too much administration is required relative to H&S’ was tempered by the agreement with ‘Administration provides the basis for addressing the physical aspects of H&S’. Therefore, the study concluded that auditing should focus on the physical process, but also give the administration process the requisite attention.

There is a total of 934 possible points across twenty elements in the current MBSA H&S Audit System. ‘Administrative and Legal Requirements’ entails a possible 244 points, which equates to 26.1% of the total possible points. Then, although it is a very important aspect of an H&S programme, ‘Education, Training and Promotion’ only entails a possible 25 points, which equates to 0.3% of the total possible points. The actual ‘Induction and Task Safety Training’ only entails a possible 8 points, which equates to 0.1% of the total possible points. Then, in terms of risk being mentioned per se there

are a possible: 5 points relative to 'CR: Hazard Identification and Risk Assessments'; 3 points relative to 'CR 29: Fire Precautions', and 2 points relative to 'Mobile Cranes'. Furthermore, in terms of indirect or implicit reference to risk being mentioned there is / are a possible: 1 point relative to 'Ergonomics'; 1 point relative to 'Noise', and 4 points relative to 'Site vehicles' (Pre-ignition checks).

Given further anecdotal evidence courtesy of contractors, which indicates that there is a plethora of documentation required relative to construction H&S, subsequent to the study conducted by Smallwood [1], a further study was conducted, the objectives being to determine the:

- Perceived importance of thirty-nine actions / beliefs / interventions / practices / states in terms of achieving optimum construction H&S, and
- Perceptions regarding H&S documentation in construction.

2. REVIEW OF THE LITERATURE

2.1 Health and Safety Legislation and Regulations

South African H&S legislation and regulations in the form of the Occupational Health and Safety Act [2], the Compensation for Occupational Injuries and Diseases Act [3], the General Safety Regulations [4], and the Construction Regulations [5], *inter alia*, collectively require a range of permit applications, notifications, appointments, inspections, investigations, meetings, and reporting, which all entail record keeping and administration.

2.2 Achieving Optimum Health and Safety

The London 2012 Olympic Park site in east London constituted a major challenge and amplified the need for client leadership as the workforce peaked at 12 000 and a total of 30 000 people will have worked on the project through its lifetime. However, through careful planning, implementation of strategies with a proven track record and clear leadership, the Olympic Delivery Authority (ODA) managed to achieve an accident frequency rate comparable to the average for all British employment, significantly better than the construction sector [6]. The H&S programme included five key elements. Safety – clear policies, risk assessments, method statements, common standards, visual standards, daily activity briefings. Health – pre-employment medical checks, prevention programme, assessment and control, health surveillance, training, emergency response. Well-being – advice, well man / woman clinics, good food strategy, campaigns, sexual health clinics, partnerships. Competence – induction, training, supervisor academy, briefings, apprenticeships, checks and records. Culture – leadership, action plans, near-miss reporting, communications, reward and recognition, climate tool.

3. RESEARCH

Ninety-two (92) Responses were received from four convenience sample strata, and included in the analysis of the data. The self-administered surveys were conducted in the Eastern Cape, Kwazulu Natal, and Western Cape provinces of South Africa.

Table 1 indicates the importance of 39 actions / beliefs / interventions / practices / states in terms of achieving optimum construction H&S on a scale of 1 (least) to 5 (very), and a MS ranging between 1.00 and 5.00. It is notable that all the MSs are above the midpoint score of 3.00, which indicates that in general the respondents perceive the actions / beliefs / interventions / practices / states as being very important as opposed to least important in terms of achieving optimum construction H&S.

It is also notable that 32 / 39 (82.1%) of the MSs are $> 4.20 \leq 5.00$, which indicates that the importance of the factors is between more than important to very / very important. A further 5 / 39 (12.9%) factors' MSs are $> 3.40 \leq 4.20$ - between important to more than important / more than important. Only 2 / 39 (%) MSs are $> 2.60 \leq 3.40$ - between less than important to important / important.

With respect to the upper half of the MS range $> 4.20 \leq 5.00$, 12 / 32 (37.5%) actions / beliefs / interventions / practices / states have MSs > 4.60 . Six are document related and six are not: H&S education; registers (Documents); H&S induction; supervisor H&S inspections; H&S file (Documents); H&S rules (Documents); hazard identification and risk assessments (HIRAs); Foreman H&S inspections; material safety data sheets (MSDSs) (Documents); H&S policy (Documents); H&S

Newsletter (Documents), and safe work procedures (SWPs) (following them). 2 / 12 are education and training related - H&S education, and H&S induction. A further 2 / 12 are inspection related - Supervisor H&S inspections, and Foreman H&S inspections. Two are risk control oriented – HIRAs, and SWPs (following them).

With respect to the lower half of the MS range $> 4.20 \leq 5.00$, 20 / 32 (62.5%) actions / beliefs / interventions / practices / states have MSs > 4.20 . Eight are document related and twelve are not: safe work procedures (SWPs) (Documents); H&S method statements (Documents); generic method statements (Documents); toolbox talks (regular); H&S Manager H&S inspections; written communication; Site Manager H&S inspections; H&S programme; H&S training; H&S management system; H&S Plan (Documents); toolbox talks (Documents); oral communication; appointments (Documents); reference to H&S upon task instruction; memoranda (Documents); H&S star grading participation; record of inspections (Documents); graphic communication, and H&S Officer H&S inspections. 2 / 20 are education and training related - toolbox talks (regular), and H&S training. 3 / 20 are inspection related - H&S Manager H&S inspections; Site Manager H&S inspections, and H&S Officer H&S inspections. 3 / 20 are communication related – written; oral, and graphic. 3 / 20 are system oriented - H&S programme, H&S management system, and H&S star grading participation. Lastly, one is risk control oriented - reference to H&S upon task instruction.

5 / 39 (12.8%) of the MSs are $> 3.40 \leq 4.20$, which indicates that the factors are between important to more than important / more than important. 2 / 5 are document related - H&S induction (Documents), and minutes of meetings (Documents). A further 2 / 5 are system oriented - H&S competition participation, and H&S meetings, and 1 / 5 is inspection related - H&S Representative H&S inspections.

The last 2 / 39 (5.1%) MSs are $> 2.60 \leq 3.40$, which indicates that the factors are between less than important to important / important, are document related - hazard identification and risk assessments (HIRAs) (Documents), and H&S Specification (Documents).

Table 1. Importance of actions / beliefs / interventions / practices / states in terms of achieving optimum construction H&S

Action / Belief / Intervention / Practice / State	Response (%)					MS	R
	Un-sure	1	2	3	Very 5		
H&S education	0.0	0.0	0.0	3.3	6.6	90.1	4.87
Registers (Documents)	0.0	0.0	4.4	35.7	12.0	84.8	4.82
H&S induction	0.0	0.0	1.1	6.5	12.0	81.5	4.75
Supervisor H&S inspections	0.0	0.0	1.1	3.3	15.4	80.2	4.75
H&S file (Documents)	0.0	0.0	3.3	42.9	18.5	76.1	4.71
H&S rules (Documents)	0.0	1.1	3.3	3.3	12.1	81.3	4.70
Hazard identification and risk assessments (HIRAs)	0.0	0.0	0.0	4.4	18.7	75.8	4.69
Foreman H&S inspections	0.0	0.0	0.0	4.4	24.4	71.1	4.67
Material safety data sheets (MSDSs) (Documents)	0.0	0.0	2.2	35.7	17.4	76.1	4.65
H&S policy (Documents)	0.0	1.1	2.2	7.6	14.1	76.1	4.64
H&S Newsletter (Documents)	0.0	2.2	15.2	28.6	20.9	71.4	4.64
Safe work procedures (SWPs) (following them)	0.0	0.0	1.1	5.6	24.4	68.9	4.61
Safe work procedures (SWPs) (Documents)	0.0	2.2	0.0	21.4	17.4	69.6	4.55
H&S method statements (Documents)	0.0	0.0	2.2	15.4	20.7	68.5	4.54
Generic method statements (Documents)	0.0	19.6	7.6	30.8	16.5	70.3	4.54
Toolbox talks (regular)	0.0	0.0	2.2	6.7	34.4	58.9	4.52
H&S Manager H&S inspections	0.0	0.0	0.0	7.8	21.1	67.8	4.52
Written communication	0.0	1.1	1.1	7.6	18.5	69.6	4.52
Site Manager H&S inspections	0.0	0.0	1.1	8.9	27.8	62.2	4.51
H&S programme	0.0	0.0	0.0	9.8	29.3	60.9	4.51

H&S training	1.1	0.0	0.0	7.8	28.9	60.0	4.48	21
H&S management system	2.2	0.0	0.0	12.0	20.7	63.0	4.48	22
H&S Plan (Documents)	0.0	1.1	2.2	7.6	31.5	58.7	4.47	23
Toolbox talks (Documents)	0.0	0.0	1.1	7.1	25.0	60.9	4.47	24
Oral communication	0.0	0.0	0.0	9.8	23.9	63.0	4.46	26
Appointments (Documents)	0.0	0.0	3.3	14.3	33.7	56.5	4.46	26
Reference to H&S upon task instruction	0.0	0.0	2.2	12.0	33.7	52.2	4.36	27
Memoranda (Documents)	0.0	0.0	8.0	14.3	31.5	53.3	4.36	28
H&S star grading participation	22.2	5.7	12.5	11.1	11.1	50.0	4.36	29
Record of inspections (Documents)	0.0	0.0	0.0	0.0	28.6	53.8	4.32	30
Graphic communication	0.0	0.0	2.2	14.3	34.1	49.5	4.30	31
H&S Officer H&S inspections	0.0	0.0	1.1	17.0	30.7	50.0	4.28	32
H&S induction (Documents)	0.0	0.0	0.0	14.3	33.3	41.1	4.11	33
H&S competition participation	33.3	6.9	9.2	16.7	16.7	25.0	3.88	34
Minutes of meetings (Documents)	4.5	0.0	4.4	35.7	31.8	27.3	3.82	35
H&S meetings	3.4	0.0	2.3	24.1	34.5	21.8	3.57	36
H&S Representative H&S inspections	2.3	1.1	2.2	26.1	33.0	20.5	3.51	37
Hazard identification and risk assessments (HIRAs) (Documents)	0.0	0.0	0.0	50.0	20.7	17.4	3.36	38
H&S Specification (Documents)	0.0	0.0	2.2	28.3	28.3	16.3	3.14	39

Table 2 indicates the extent to which respondents concur with various statements relative to construction H&S on a scale of strongly disagree to strongly agree, and MSs between 1.00 and 5.00. It is notable that all the statements have MSs > 3.00, which indicates that in general, the respondents agreed with the statements.

The MSs of 7 / 22 (31.8%) statements are $> 4.20 \leq 5.00$, which indicates that the concurrence is between agree to strongly agree / strongly agree. In summary: thick / lengthy documents, and complex documents (could be simplified) are not in the interest of H&S; too much documentation results in people ‘going through the motions’ (ticking boxes), copying and pasting, and not actually addressing the risk.

The MSs of 12 / 22 (54.6%) of the statements are $> 3.40 \leq 4.20$, which indicates that the concurrence is between neutral to agree / agree. In summary: too much documentation results in ‘window dressing’, ‘tearoom tick fever’, and shifts the focus from the physical aspects of H&S; thick documents marginalise the locating of information; documents contain generic and duplicated information, and are vague; the users of documents should be considered; documents could be improved; the focus is on documentation, documentary evidence, and not the physical process; HURA templates are complex, and H&S has become a ‘paperwork game’.

The MSs of 3 / 22 (13.6%) of the statements are $> 2.60 \leq 3.40$, which indicates that the concurrence is between disagree to neutral / neutral. In summary: there is too much documentation relative to H&S, and documentation assures / ensures that processes are duly undertaken.

Table 2. Extent of agreement with statements relative to construction H&S

Statement	Response (%)						MS
	Unsure	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	
Thick documents discourage people from reading them	0.0	0.0	3.3	6.7	44.4	45.6	4.32

Documentation could be simplified and made more ‘user friendly’	1.1	0.0	3.4	11.4	35.2	48.9	4.31
Documentation should be kept to a minimum, with concise, clear and relevant information included	0.0	1.1	1.1	7.8	46.7	43.3	4.30
People tick boxes without really understanding the related processes	0.0	2.2	2.2	4.4	49.5	41.8	4.26
People tick boxes without really undertaking the related processes	0.0	1.1	0.0	8.9	52.2	37.8	4.26
Too much documentation results in ‘copying and pasting’	1.1	4.4	1.1	3.3	50.0	40.0	4.21
Many organisations are just producing documentation, rather than addressing risk	3.3	1.1	3.3	8.9	44.4	38.9	4.21
Too much documentation results in ‘window dressing’	4.4	4.4	2.2	9.9	41.8	37.4	4.10
Too much documentation results in ‘tearoom tick fever’	5.6	3.4	2.2	10.1	44.9	33.7	4.10
Thick documents make finding specific piece of information much more difficult	0.0	2.2	3.3	15.4	42.9	36.3	4.08
Documents would communicate more efficiently using flow charts, bullet points, drawings and pictures, would make documentation more understandable	0.0	0.0	1.1	25.3	38.5	35.2	4.08
Documents contain a significant amount of generic and duplicate information	0.0	0.0	4.4	12.2	57.8	25.6	4.04
The criteria of ease of reading and understanding are frequently not addressed by the authors of documents	1.1	1.1	2.2	19.1	50.6	25.8	3.99
Documentary evidence is the primary concern of management	0.0	0.0	10.2	13.6	50.0	26.1	3.92
Too much documentation shifts the focus from the physical aspects of H&S	0.0	3.4	10.1	10.1	49.4	27.0	3.87
Documents contain vague words such as ‘appropriate’, ‘adequate’, ‘as necessary’, ‘sufficient’ and ‘suitable’	2.2	0.0	10.0	16.7	48.9	22.2	3.85
The documentation is right, but the physical process is not	2.2	4.4	7.8	12.2	50.0	23.3	3.82
H&S has become a ‘paperwork game’	1.1	4.4	13.3	7.8	45.6	27.8	3.80
HIRA templates are overly complex	3.4	1.1	12.4	29.2	33.7	20.2	3.62
There is too much documentation relative to H&S	0.0	4.4	27.5	19.8	34.1	14.3	3.26
Documentation assures that processes are duly undertaken	0.0	6.7	23.6	22.5	34.8	12.4	3.22
Documentation ensures that processes have been duly undertaken	0.0	5.6	24.4	26.7	32.2	11.1	3.19

4. CONCLUSIONS

In addition to a range of H&S documentation, a range of actions / beliefs / interventions / practices / states are important in terms of achieving optimum construction H&S. In terms of non-H&S documentation, H&S training, H&S induction, inspections by various stakeholders, HIRAs, following SWPs, toolbox talks (regular), written, oral, and graphic communication, H&S programme, H&S

training, H&S management system, reference to H&S upon task instruction, and H&S star grading participation predominate. In terms of H&S documentation, registers, H&S File, H&S rules, MSDSSs, H&S policy, H&S Newsletter, SWPs, H&S method statements, generic method statements, H&S Plan, toolbox talks, appointments, memoranda, and record of inspections predominate. Therefore, it can be concluded that both H&S documentation and a range of actions / beliefs / interventions / practices / states are important in terms of achieving optimum construction H&S. Furthermore, H&S documentation facilitates and assists planning, organising, leading, controlling, and coordinating of H&S.

The rankings of H&S documents indicate that some documents are more important than others.

Based upon the degree of consensus with various statements, the following can be concluded relative to current H&S documentation: it is inappropriate in that it can be complex, generic, lengthy, onerous, repetitive (duplicative), and vague; it engenders dubious practices; it generally ‘does not add the potential value’; it shifts the focus from the physical process, and it could be improved.

5. RECOMMENDATIONS

Industry associations should review their ‘audit system’ to interrogate the allocation of points relative to H&S documentation vis-à-vis the physical process, and actions, interventions, and practices. An example includes toolbox talks (regular) ranked sixteenth, vis-à-vis toolbox talks (documents), ranked twenty-fourth.

The relative importance of H&S documents should be noted, digested, and deliberated in terms of their ‘value’ as assigned by the ‘audit system’ score.

H&S documents must reflect the intention of the requirement. For example, an H&S specification must record, among other, the client’s requirements, and residual hazards and risks, and not constitute a regurgitation of the Occupational Health and Safety Act, and the Construction Regulations. The H&S specification, H&S plan, and H&S file are prime examples of documents for which guidelines should be provided by the Department of Labour, or by the Construction Industry Development Board (cidb).

The synergy between H&S documentation, and actions, interventions, and practices should be investigated, digested, and focused upon. For example, HIRAs are ranked seventh, yet HIRAs (documents) are ranked thirty-eighth. The former is the more critical, especially if undertaken just prior to commencing an activity, and even more so, if reinforced by a toolbox talk (ranked sixteenth). A further example is that of SWPs (following them) ranked twelfth, followed by SWPs (documents) ranked thirteenth. The issue is that a copy of the SWP (document) should be on-site where the activity is underway, and referred to, not just filed in the so-called H&S file.

‘Audits’, or rather inspections, should focus more on the physical process, actions, interventions, and practices, than documentation.

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Industry 4.0 & Construction H&S: Comparative Perceptions

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Abstract: Historical construction health and safety (H&S) challenges, in terms of a range of resources and issues, continue to be experienced, namely design process-related hazards are encountered on site, workers are unaware of the hazards and risks related to the construction process and its activities, activities are commenced on site without adequate hazard identification and risk assessments (HIRAs), difficulty is experienced in terms of real time monitoring of construction-related activities, workers handle heavy materials, plant, and equipment, and ultimately the experience of injuries. Given the abovementioned, and the advent of Industry 4.0, a quantitative study, which entailed the completion of a self-administered questionnaire online, was conducted among registered professional (Pr) and candidate Construction H&S Agents, to determine the potential of Industry 4.0 to contribute to resolving the challenges cited. The findings indicate that Industry 4.0 technologies such as augmented reality (AR), drone technology, virtual reality (VR), VR based H&S training, and wearable technology / sensors have the potential to resolve the cited H&S challenges as experienced in construction. Conclusions include that Industry 4.0 technologies can finally address the persistent H&S challenges experienced in construction. Recommendations include: employer associations, professional associations, and statutory councils should raise the level of awareness relative to the potential implementation of Industry 4.0 relative to H&S in construction; case studies should be documented and shared; tertiary construction management education programmes should integrate Industry 4.0 into all possible modules, especially H&S-related modules, and continuing professional development (CPD) H&S should address Industry 4.0.

Key words: Construction, Health and Safety, Industry 4.0, Performance

1. INTRODUCTION

The fourth industrial revolution, or Industry 4.0, is gaining momentum, and entails a paradigm shift that will have a significant impact on the management of occupational H&S. The adoption of Industry 4.0 related technology offers the construction industry a chance to improve efficiency, productivity, and H&S. The Construction Industry Development Board (cidb) highlighted the considerable number of accidents, fatalities, and other injuries that occur in the South African construction industry in their report ‘Construction Health & Safety Status & Recommendations’ [1]. Historically, construction has experienced more deaths and injuries than any other industry. Although not inherently dangerous, construction is known as a hazardous industry that presents many factors that are potentially dangerous to workers. Park and Kim reveal that most accidents associated with construction work were attributable to a lack of proactive and preventive measures such as H&S workforce training, HIRA, H&S awareness and education [2]. “At the organisational and site level, poor construction H&S performance is attributable to a lack of management commitment, inadequate supervision and inadequate or a lack of H&S training” (Construction Industry Development Board (cidb), 2009) [1]. Construction H&S monitoring relies heavily on manual observation to monitor and identify any potential hazards that may expose workers to H&S risks. This can become challenging as construction sites must be continuously monitored to detect unhealthy and unsafe working conditions in order to protect workers from potential injuries and fatal accidents. Industry 4.0 brings technology such as drones, AR, VR, and wearable sensors that can mitigate many of these challenges. Considering the numerous challenges experienced in construction, H&S included, it is inevitable that Industry 4.0 is considered to overcome these.

According to Autodesk & CIOB, digital technologies are transforming every industry, and construction is no exception [3]. Given the continuing poor H&S performance in South African construction, the aim of the study was to evolve an Industry 4.0 response to H&S challenges encountered in construction to determine the:

- Frequency at which ten H&S phenomena are experienced on projects;
- Potential of Industry 4.0 technologies to improve H&S performance;
- Potential of AR to assist designers and workers in identifying design process-related hazards on site;
- Potential of AR to assist designers in identifying design process-related hazards on site;
- Potential of using VR systems as a method of training to enable workers to identify potential hazards and mitigate risks on site;
- Potential of using drone technology to improve HIRA before activities commence on site;
- Potential of using drone technology to assist real time monitoring of construction activities;
- Potential of equipping workers with wearable technology / sensors to mitigate the hazards and risk accompanying the handling of heavy materials, plant, and equipment, and
- Potential of Industry 4.0 technologies to reduce the occurrence of H&S phenomena.

2. REVIEW OF THE LITERATURE

2.1 The potential of VR and AR in H&S Management

In recent years visualisation technologies such as VR and AR have been developed and used to improve construction productivity, H&S, and quality [4]. Both AR and VR have the potential to improve on site construction processes [4]. According to Park et al., AR based applications and systems have been developed to improve on-site tasks such as data visualisation, work inspection, and checking for omissions. These systems have improved on-site H&S performance to some extent [5]. According to Silliker, VR is rapidly gaining traction as a training tool in occupational H&S [6]. VR technology provides a virtual environment that allows users to immerse themselves in a virtual world that uses sight, sound, and sometimes motion to provide a realistic experience [6]. Wang et al. state that the construction sector is a high-risk industry where accident rates remain high [7]. It was highlighted that some of the reasons leading to the high level of risk include limited H&S knowledge of on-site workers and lack of H&S awareness and training of these individuals. Construction H&S training has traditionally been carried out in a classroom setting with slide presentations or videos. However, the H&S information provided in the presentations and videos often do not represent real construction site conditions [7]. A study conducted by Sacks et al. determined that VR-based training was more effective than traditional H&S training methods, which made use of classrooms and slide presentations [8]. The study determined that workers had better recall in identifying and assessing construction H&S risks, than they would have using traditional conventional methods. According to Wang et al., there are currently a few VR-related technologies that have been developed to improve the current construction H&S training practices [7]. VR is becoming more popular in the occupational H&S space as it provides a method of training workers relative to their actual job tasks in a safe environment [6].

2.2 The potential of drones to improve real time monitoring and HIRAs

A study conducted by Gheisari and Esmaeili [9] determined that using unmanned aerial systems (UASs) commonly referred to as ‘drones’, to monitor construction activities could help identify potential on site hazards and therefore improve H&S management. Tatum and Liu [10] determined that the construction industry is already making use of drones to carry out various tasks related to the construction processes and its activities. UASs provide an effective solution to carry out real-time monitoring and improve H&S monitoring and control practices on site [9]. According to Alizadehsalehi et al. [11], UAS technologies can easily monitor the entire construction site by flying around the construction area under a H&S manager’s control and transmit real-time information for inspecting H&S issues related to the project. UAS technology can enable H&S managers to identify hazards at different stages of the project and develop suitable mitigation strategies [11]. Borck states that in addition to remote H&S inspections, drones are being used for many other tasks in the construction industry, including the monitoring of construction work without disrupting ongoing work; assessing and

determining the integrity of structures; identifying problems before they develop through the use of maintenance assessments; facilitating communication and surveillance; documenting jobsite conditions from the commencement to the end of the project, and increasing the scope and frequency of inspections [12].

2.3 The potential of wearable technology / sensors in H&S management

Seo et al. [13] state that due to the hazardous working environments on construction sites, workers are frequently faced with potential H&S risks throughout the entire construction process. Nath et al. [14] state that “construction works are labour-intensive and often stipulate the workers to go beyond their natural physical limits to cope up with the increasing complexities and challenges of their assigned tasks”. Traditional approaches of measuring H&S performance indicators are largely manual in nature [15]. To overcome these limitations of manual efforts, automated H&S monitoring is considered one of the most promising methods for accurate and continuous monitoring of H&S performance on construction sites [15]. Wearable technologies can enable the continuous monitoring of a wide range of vital signals which can provide early warning systems for workers with high-risk health issues [16]. A study conducted by Nath et al. [14] determined that wearable technology was able to prevent work related-injuries and fatalities by ergonomically designing the work environment based on previous data collected [14]. The use of this technology was able to identify and eliminate the ergonomic risks at the source to prevent similar incident from re-occurring [14].

3. RESEARCH

The exploratory study entailed the completion of a self-administered online questionnaire survey. The sample strata for the research study was limited to 92 Professional Construction Health and Safety Agents (Pr CHSAs), and 139 Candidate (Can) CHSAs registered with the South African Council for the Project and Construction Management Professions (SACPCMP). The questionnaire consisted of eighteen questions – seventeen closed ended, and one open-ended. Twelve of the close ended questions were Likert scale type questions, and five were demographics related. 63 Responses were included in the analysis of the data, which entailed the computation of frequencies, and a measure of central tendency in the form of a mean score (MS), to enable the interpretation of percentage responses to Likert point scale type questions, and the ranking of variables. The 63 responses equate to a response rate of 31.2%. As stated in the ‘Introduction’ above, in terms of the study reported on, the following Industry 4.0 technologies were considered: AR; drones; VR, and wearable sensors.

Table 1 indicates the frequency at which ten H&S phenomena are experienced on projects in terms of MSs between 1.00 and 5.00, based upon percentage responses to a scale of never to constantly. It is notable that 7 / 10 (70.0%) of the mean MSs are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the phenomena to be experienced on projects. The mean MS of the phenomenon ‘similar incidents reoccur’ falls on the cut point. It is notable that no phenomena are experienced between often to constantly / constantly (MSs $> 4.20 \leq 5.00$). 4 / 10 (40.0%) of the mean MSs are $> 3.40 \leq 4.20$, which indicates the frequency is between sometimes too often / often - workers handle heavy materials, plant, and equipment, delays, on site hazards, and difficulty is experienced in terms of real time monitoring of construction-related activities. The remaining 6 / 10 (60.0%) of the mean MSs are $> 2.60 \leq 3.40$, which indicates the phenomena are experienced between rarely to sometimes / sometimes - activities are commenced on site without adequate HIRAs, workers are unaware of the hazards and risks related to the construction process and its activities, design process-related hazards are encountered on site, similar incidents reoccur, accidents, and injuries.

A notable difference between the sample strata is that six of the Pr CHSAs’ MS are higher than the highest Can CHSA MS. There are no major differences between the two in terms of the ranks achieved by the phenomena.

Table 1. Frequency at which ten H&S phenomena are experienced on projects

Phenomenon	Can CHSAs		Pr CHSAs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Workers handle heavy materials, plant, and equipment	3.50	1	3.70	2	3.60	1
Delays	3.20	3	3.85	1	3.54	2
On site hazards	3.28	2	3.70	3	3.50	3
Difficulty is experienced in terms of real time monitoring of construction-related activities	3.17	4	3.66	4	3.42	4
Activities are commenced on site without adequate HIRAs	3.11	6	3.64	5	3.39	5
Workers are unaware of the hazards and risks related to the construction process and its activities	3.00	8	3.53	6	3.27	6
Design process-related hazards are encountered on site	3.14	5	3.27	7	3.21	7
Similar incidents reoccur	3.03	7	2.97	8	3.00	8
Accidents	2.86	9	2.88	9	2.87	9
Injuries	2.73	10	2.88	10	2.81	10

Table 2 indicates the respondents' self-rating of their awareness of / exposure to four Industry 4.0 technologies in terms of MSs ranging between 1.00 and 5.00, based upon percentage responses to a scale of 1 (limited) to 5 (extensive). It is notable that none of the mean MSs are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to rate themselves below average. Only 1 / 4 (25.0%) mean MSs are $> 2.60 \leq 3.40$, which indicates a rating of below average to average / average - drones. The remaining 3 / 4 (75.0%) mean MSs are $> 1.80 \leq 2.60$, which indicates a rating of limited to below average / below average - VR, wearable technology / sensors, and AR. The findings indicate that the respondents have generally a low level of awareness / had limited exposure to the four technologies to date.

A notable difference between the sample strata is that three of the Can CHSAs' MS are higher than the corresponding Pr CHSA MSs. It is notable that the ranks are identical for the two sample strata and the mean.

Table 2. Respondents' self-rating of their awareness of / exposure to four Industry 4.0 technologies

Aspect	Can CHSAs		Pr CHSAs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Drones	2.64	1	2.69	1	2.67	1
Virtual Reality	2.52	2	2.13	2	2.31	2
Wearable technology / sensors	2.39	3	2.03	3	2.20	3
Augmented Reality	2.13	4	2.03	4	2.07	4

Table 3 indicates the potential of Industry 4.0 technologies to improve H&S performance in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. It is notable that all the MSs are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the potential to be above average. Although the Pr CHSAs' MS (4.19) is marginally below the lower point of the upper range, all the MSs are $> 3.40 \leq 4.20$, which indicates between potential to near major / near major potential. Despite the respondents' generally low self-rating of their awareness of / exposure to the identified four Industry 4.0 technologies, they recognise the potential of Industry 4.0 technologies to improve H&S performance as per the literature. A notable difference between the sample strata is that the Pr CHSAs' MS is higher than the Can CHSA MS.

Table 3. Potential of Industry 4.0 technologies to improve H&S performance

MS		
Can CHSAs	Pr CHSAs	Mean
4.00	4.19	4.11

Table 4 indicates the potential of VR to improve aspects of H&S performance in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. It is notable that all the MSs for both sample strata (100.0%) are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the potential to be above average. 3 / 3 (100.0%) of the mean MSs are $> 3.40 \leq 4.20$, which indicates between potential to near major / near major potential - assist designers to identify potential design process-related hazards on site, enable workers to identify potential hazards and mitigate risks on site, and H&S training. Despite the respondents' generally low self-rating of their awareness of / exposure to the identified four Industry 4.0 technologies, they recognise the potential of VR to improve aspects of H&S performance as per the literature.

Table 4. Potential of VR to improve aspects of H&S performance

Aspect	Can CHSAs		Pr CHSAs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Assist designers to identify potential design process-related hazards on site	4.12	3	4.34	1	4.24	1
Enable workers to identify potential hazards and mitigate risks on site	4.32	1	4.06	3	4.18	2
H&S training	4.29	2	4.06	2	4.16	3

Table 5 indicates the potential of AR to assist workers to identify potential design process-related hazards on site in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. It is notable that all the MSs are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the potential to be above average. All the MSs are $> 3.40 \leq 4.20$, which indicates between potential to near major / near major. Despite the respondents' generally low self-rating of their awareness of / exposure to the identified four Industry 4.0 technologies, they recognise the potential of AR to improve the aspects of H&S performance as per the literature. A notable difference between the sample strata is that the Can CHSAs' MS is higher than the Pr CHSAs' MS.

Table 5. Potential of AR to assist workers to identify potential design process-related hazards on site

MS		
Can CHSAs	Pr CHSAs	Mean
4.05	3.82	3.92

Table 6 indicates the potential of drones to improve aspects of H&S performance in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. It is notable that all the MSs for both sample strata (100.0%) are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the potential to be above average. 'Assist in terms of real time monitoring of construction activities' has a mean MS $> 4.20 \leq 5.00$, which indicates between near major to major / major potential, whereas 'Improve HIRAs before activities commence on site' has a mean MS $> 3.40 \leq 4.20$, which indicates between potential to near major / near major potential. Despite the respondents' generally low self-rating of their awareness of / exposure to the identified four Industry 4.0 technologies, they recognise the potential of drones to improve the aspects of H&S performance as per the literature. There are no major differences between the two in terms of the ranks achieved by the aspects.

Table 6. Potential of drones to improve aspects of H&S performance

Aspect	Can CHSAs		Pr CHSAs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Assist in terms of real time monitoring of construction activities	4.18	1	4.25	1	4.22	1
Improve HIRAs before activities commence on site	3.82	2	3.91	2	3.87	2

Table 7 indicates the potential of wearable technology / sensors to mitigate the hazards and risk accompanying the handling of heavy plant, equipment, and materials in terms of percentage responses to a scale of 1 (minor) to 5 (major), and a MS ranging between 1.00 and 5.00. It is notable that all the MSs for both sample strata (100.0%) are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the potential to be above average. Both mean MSs are $> 3.40 \leq 4.20$, which indicates between potential to near major / near major potential. Despite the respondents' generally low self-rating of their awareness of / exposure to the identified four Industry 4.0 technologies, they recognise the potential of wearable technology / sensors to mitigate the hazards and risk and improve the aspects of H&S performance as per the literature. It is notable that the MSs for the Pr CHSAs are the same for both aspects - heavy plant, and equipment, and heavy materials.

Table 7. Potential of wearable technology / sensors to mitigate the hazards and risk accompanying the handling of heavy plant, equipment, and materials

Aspect	Can CHSAs		Pr CHSAs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Heavy plant, and equipment	3.62	1	3.72	2	3.67	1
Heavy materials	3.50	2	3.72	1	3.62	2

Table 8 indicates the potential of four Industry 4.0 technologies to reduce the occurrence of H&S phenomena in terms of MSs ranging between 1.00 and 5.00, based upon percentage responses to a scale of 1 (minor) to 5 (major). It is notable that all MSs (100.0%) are above the midpoint of 3.00, which indicates that in general the respondents can be deemed to perceive the potential to be above average. It is notable that no mean MSs are $> 4.20 \leq 5.00$ - between near major to major / major potential – observation. 12 / 13 (92.3%) mean MSs are $> 3.40 \leq 4.20$, which indicates between potential to near major / near major potential. 3 / 12 (25.0%) of these phenomena fall in the upper half of the range, namely $> 3.80 \leq 4.20$ – risks, hazards, and accidents. The remaining 9 / 12 (75.0%) mean MSs are $> 3.40 \leq 3.80$, two of which have mean MSs of 3.79, 0.01 below 3.80 – injuries, and unsafe acts. Despite the respondents' generally low self-rating of their awareness of / exposure to the identified four Industry 4.0 technologies, they recognise the potential of Industry 4.0 technologies to improve the stated H&S-related interventions / goals.

A notable difference between the sample strata is that eight of the Pr CHSAs' MS are higher than the highest Can CHSA MS. There are no major differences between the two in terms of the ranks achieved by the first six phenomena.

Table 8. Potential of Industry 4.0 technologies to reduce the occurrence of H&S phenomena

Phenomenon	Can CHSAs		Pr CHSAs		Mean	
	MS	Rank	MS	Rank	MS	Rank
Risks	3.79	2	4.13	1	3.97	1
Hazards	3.79	3	4.06	2	3.93	2
Accidents	3.85	1	4.00	4	3.93	3
Injuries	3.63	4	3.94	7	3.79	4
Unsafe acts	3.62	5	3.94	6	3.79	5
Unsafe working conditions	3.46	8	3.97	5	3.74	6
Difficulty in terms of monitoring workers	3.43	10	4.00	3	3.73	7
Difficulty in terms of monitoring on-site activities	3.52	7	3.88	8	3.72	8
Similar incidents reoccurring	3.54	6	3.77	9	3.66	9
Sprains and strains among workers	3.39	11	3.71	10	3.56	10
Unhealthy working conditions	3.29	12	3.60	12	3.45	11
A shortage of workers with the necessary skills	3.44	9	3.43	13	3.44	12
Delays	3.11	13	3.62	11	3.37	13

4. CONCLUSION

Given the frequency at which H&S phenomena are experienced on projects by respondents, it can be concluded that the respondents experience the range of these phenomena on projects. It can further be concluded that there is a need for H&S improvement, and a need for the implementation of Industry 4.0 related technologies.

In light of the respondents' self-rating of their awareness of / exposure to four Industry 4.0 technologies, it can be concluded that there is a need for interventions by government, statutory bodies, and tertiary education programmes to raise the level of awareness, and to integrate such technologies into built environment / construction education and training.

In general, it can be concluded that there is a need for the implementation of Industry 4.0 in construction given the potential of Industry 4.0 technologies to improve H&S performance.

Given the potential of the following Industry 4.0-related technologies to improve H&S performance it can be concluded that there is a need for their implementation: VR in terms of assisting designers to identify potential design process-related hazards on site, enabling workers to identify potential hazards and mitigate risks on site, and H&S training; AR to improve H&S performance by assisting workers to identify potential design process-related hazards on site; drones in terms of real time monitoring of construction activities, and improved HIRAs before activities commence on site, and wearable technology / sensors to mitigate the hazards and risk accompanying the handling of heavy plant, equipment, and materials.

Industry 4.0 technologies such as VR, AR, drones, and wearable technology / sensors have the potential to contribute to resolving many of the H&S challenges experienced in construction.

5. RECOMMENDATIONS

Built environment-related tertiary education must include, or rather embed Industry 4.0 in their programmes, and H&S-related modules should address the role of Industry 4.0 technologies.

Construction employer associations, and built environment associations and statutory councils must promote, and preferably provide H&S-Industry 4.0 continuing professional development (CPD), and evolve related guidelines and practice notes.

The Construction Industry Development Board (cidb) should evolve a position paper relative to Industry 4.0 in construction, and deliberate the development of a related industry standard.

Researchers should actively conduct and document H&S-related Industry 4.0 case studies to record the benefits of implementing Industry 4.0 technologies.

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Reliability and responsiveness of Equivital Lifemonitor and photoplethysmography based wristwatch for the assessment of physiological parameters during a simulated fatigue task

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Abstract: **Objective:** To investigate test-retest reliability and responsiveness of Equivital Lifemonitor and photoplethysmography based wristwatch tools in assessing physiological parameters during a simulated fatigue task. **Methods:** Ten university students (Mean age, 30.6 ± 1.7 years) participated in this pilot study. Participants were asked to perform a 30-minute of a simulated fatigue task in an experimental setup in a lab. The physiological parameters (e.g., heart rate, heart rate variability, respiratory rate, electrodermal activity, and skin temperature) were measured at baseline and immediately after the fatigue task. An intraclass correlation coefficient ($ICC_{2,1}$) was used to evaluate the test-retest reliability of each tool in assessing physiological measures. In addition, the responsiveness of each tool to measure changes from baseline to posttest was calculated using a standardized response mean. **Results:** The Equivital Lifemonitor has shown good to excellent test-retest reliability for the assessment of heart rate (ICC , 0.97), heart rate variability (ICC , 0.86), respiratory rate (ICC , 0.77), and local skin temperature (ICC , 0.76). However, photoplethysmography based wristwatch showed moderate to good test-retest reliability for the assessment of heart rate (ICC , 0.71), heart rate variability (ICC , 0.73), electrodermal activity (ICC , 0.80), and skin temperature (ICC , 0.72). A large standardized response mean (>0.8) indicates that both tools can capture the changes in heart rate, heart rate variability, respiratory rate, skin temperature, and electrodermal activity after a 30-minute of fatigue task. **Conclusions:** The Equivital Lifemonitor and photoplethysmography based wristwatch devices are reliable in measuring physiological parameters after the fatigue task. Additionally, both devices can capture the fatigue response after a simulated construction task. Future field studies with a larger sample should investigate the sensitivity and validity of these tools in measuring physiological parameters for fatigue assessment at construction sites.

Keywords: Heart rate, reliability, skin temperature, heart rate variability, construction workers

1. INTRODUCTION

Construction industry is the most vulnerable for workplace accidents given the extremely exhausting nature of construction tasks [1]. Additionally, construction tasks are often performed under very hot and humid conditions [2]. Therefore, construction workers are prone to develop the risk of physical fatigue and fatigue-related workplace accidents [3]. Besides the general workforce, fatigue is a more critical issue for older workers who are more prone to fatigue development because of decreased cardiac output, muscle mass, and physical working capacity [4]. Since about 56% of the workers are 50 years and older in regions like Hong Kong, it has become a matter of huge concern [5]. Therefore, early monitoring of fatigue has become necessary to prevent undesirable workplace accidents in construction workers.

Fatigue is the leading cause of construction accidents [6-8]. Mostly, construction accidents are associated with poor work behaviour, poor design (of material, machinery, or workplace), and other factors (such as hot weather conditions) [9,10]. Past studies have pointed out despite significant advancements in technology, training, and communication in the last few decades, the enormous amount of accidents in construction workers might be related to poor work behavior results fatigue [11,12]. A previous study found fatigue to be the topmost reason for workplace accidents at the construction sites [13]. Another study acknowledged fatigue to be one of the primary causes of work place accidents in the building construction industry [14]. Similalry, Wong et al. [15] found fatigue to be one of the important risk factors for falls from height accidents in Hong Kong. In short, monitoring and management of fatigue has become a matter for the safety of construction workers.

Various physiological parameters, including heart rate (HR), heart rate variability (HRV), respiratory rate, electrodermal activity, and skin temperature may be used to monitor fatigue in construction workers [16,17]. For instance, Yi et al. [18] and Aryal et al. [19] have assessed physical fatigue in construction workers using HR metric, and HR and skin temperature metrics, respectively. Recently, Anwer et al. [17] also found positive correlations between physiological parameters (including HR, respiratory rate, and skin temperature) and subjective fatigue scores.

The development of new wearable technologies and recent advancements in physiology have given the opportunities to enable the objective, smooth, and steady monitoring of fatigue during construction tasks. For instance, the Equivital Lifemonitor is a wearable ambulatory device used to measure HR, HRV, skin temperature, and respiratory rate via chest-worn textile-based embedded sensors [20]. Previous studies have indicated the accuracy and validity of Equivital Lifemonitor in monitoring HR, HRV, skin temperature, and respiratory rate [20-22]. However, only one study tested the reliability of this device to monitor physiological parameters [21]. Another wearable device such as photoplethysmography (PPG) based wristwatch has also been used to monitor HR, HRV, and skin temperature by emitting light from light-emitting diodes and then detecting skin blood flow signals by photoreceptors [23,24]. PPG can also measure the electrodermal activity of the skin by two electro-conductors [17]. Previous studies have found high accuracy and validity of PPG based wristwatch to monitor HR, HRV, electrodermal activity, and skin temperature [24-27].

Although Equivital Lifemonitor [21,22,28] and PPG based wristwatch [24-27,29] have been validated in many studies, the reliability and responsiveness of these devices have not been well tested during construction tasks. Additionally, some prior reports found that Equivital LifeMonitor and PPG based wristwatch had high movement artifacts [20,24], and therefore, it may affect the usage of these devices during construction tasks. Therefore, the current pilot study aimed to investigate test-retest reliability and responsiveness of the Equivital Lifemonitor and photoplethysmography based wristwatch in assessing physiological measures during a simulated fatigue task.

2. METHODS

2.1. Participants

Ten healthy university students (Mean age, 30.6 ± 1.7 years) participated in this pilot study. Individuals with a history of musculoskeletal disorders, neurological disorders, or cardio-pulmonary diseases were excluded. The study followed the guidelines of the Declaration of Helsinki, and the protocol was approved by the Ethical Committee of the University (Reference Number: HSEARS20190824004). The written informed consent of the participant was obtained before data collection. A self-reported questionnaire was used to collect demographics and physical health.

2.2. Simulated fatigue task

Participants were performed a manual material handling task to develop self-identified physical exertion. Participants were asked to simulate a manual material handling task by carrying a wooden box of 15 kg from one point to another over a distance of 10-meter and continued this task for a 30-minute. This load was a typical weight handled by construction workers [30]. The simulated fatigue task was conducted using a modified experimental setup as published in the past studies [17,19,31]. Specifically,

there was a two point (pickup and dropoff) over the distance of 10-mtere. Participants were asked to pickup the loaded wooden box from the pickup point and took it to dropoff point and after 1-minute of rest they continued this task till they achieved a self-identified fatigue level > 15 out 20 on Borg-20 scale [32].

2.3. Measurements of physiological parameters

HR, HRV, respiratory rate, electrodermal activity, and skin temperature parameters were measured at baseline and immediately after the 30-minute of fatigue task. These parameters were measured using the Equivital Lifemonitor system and a PPG based wristwatch (Figure 1). The physiological parameters were measured twice over 10 minutes of rest to determine the test-retest reliability of two devices. Additionally, the parameters were measured immediately after the fatigue task to determine the responsiveness of both devices in assessing physical fatigue.

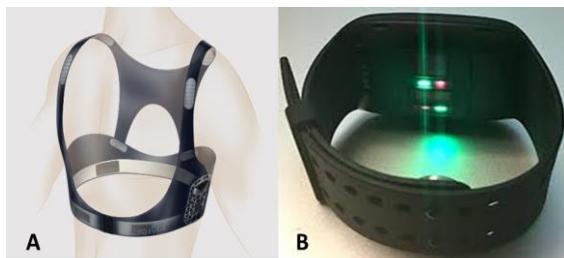


Figure 1. (A) Equivital Lifemonitor vest, (B) E4 photoplethysmography (PPG) wristwatch (Picture reproduced with permission)

2.4. Statistical analysis

The SPSS version 22 (IBM Inc., Chicago, IL) was used for conducting the statistical analysis. Descriptive statistics (mean and standard error), and an intraclass correlation coefficient ($ICC_{2,1}$) were used to evaluate the test-retest reliability of each device to assess physiological measures. In addition, the responsiveness of each device to measure changes from baseline to posttest was calculated using the standardized response mean (SRM). The level of responsiveness was determined as follows: SRM > 0.8 (large), 0.5 to 0.8 (moderate), and 0.2 to 0.5 (small) [33]. The data was statistically significant if alpha level = 0.05.

3. RESULTS

Table 1 illustrates the baseline and post-fatigue data of all variables. Mean HR was increased by about 49 beats/minute after the fatigue task. Similarly, the mean respiratory rate was increased to about 13 rates/min after the fatigue task. The mean changes in the electrodermal activity and skin temperature after the fatigue task were $2.3 \mu\text{S}/\text{cm}$ and 2°C , respectively.

Table 2 indicates the test-retest reliability and responsiveness of two devices in assessing the physiological parameters after a fatigue task. The Equivital Lifemonitor has shown good to excellent test-retest reliability for the assessments of HR ($ICC, 0.97$), HRV ($ICC, 0.86$), respiratory rate ($ICC, 0.77$), and skin temperature ($ICC, 0.76$). However, PPG based wristwatch showed moderate to good test-retest reliability for the assessments of HR ($ICC, 0.71$), HRV ($ICC, 0.73$), electrodermal activity ($ICC, 0.80$), and local skin temperature ($ICC, 0.72$). In addition, both devices showed a large SRM (>0.8) to measure cardiorespiratory and thermoregulatory parameters after the fatigue task.

Figure 2 depicts the test-retest reliability of the Equivital Lifemonitor and PPG based wristwatch in assessing HR and HRV. The Bland–Altman plots indicate that most of the scores were not beyond the limits of agreement.

Table 1. Descriptive Statistics

	Mean	Std. Error	95% CI
Age (Y)	30.6	1.7	25.6 – 33.7
Height (m)	1.7	.03	1.6 – 1.7
Weight (kg)	68.5	1.2	63.6 – 71.6
Heart rate at baseline, Beats/minute	74.1	5.9	57.8 – 86.4
Heart rate at post-fatigue, Beats/minute	122.9	6.1	106.1 – 139.6
Respiratory rate at baseline, N	15.1	1.6	14.7 – 20.5
Respiratory rate at post-fatigue, N	28.2	2.9	20.3 – 36.1
Skin temperature at baseline, °C	32.8	.87	31.6 – 32.9
Skin temperature at post-fatigue, °C	34.8	.50	33.4 – 36.2
Electrodermal activity at baseline, μ S/cm	2.83	.67	.19 – .55
Electrodermal activity at post-fatigue, μ S/cm	5.1	1.9	-.16 – 10.4

Table 2. Test-retest reliability and responsiveness of Equivital Lifemonitor and photoplethysmography (PPG) based wristwatch in assessing heart rate (HR), heart rate variability (HRV), respiratory rate, skin temperature, and electrodermal activity

Equivital Lifemonitor				
	1 st Test	Re-test	ICC (95% CI)	SRM (95% CI)
HR	74.1 (5.9)	73.3 (6.7)	0.97 (0.92 – 0.98)	3.48 (2.72 to 4.90)
HRV	0.73 (0.02)	0.72 (0.01)	0.86 (0.66 – 0.94)	1.20 (0.90 to 1.5)
Skin temperature	32.8 (0.87)	32.9 (0.93)	0.76 (0.43 – 0.90)	1.80 (1.40 to 2.65)
Respiratory rate	15.1 (1.6)	14.9 (1.5)	0.77 (0.46 – 0.90)	1.40 (0.95 to 1.85)
PPG Wristwatch				
	1 st Test	Re-test	ICC (95% CI)	SRM (95% CI)
HR	72.3 (3.10)	73.7 (2.94)	0.71 (0.34 – 0.87)	3.21 (2.00 to 4.24)
HRV	0.83 (0.05)	0.82 (0.04)	0.73 (0.38 – 0.88)	1.10 (0.90 to 1.3)
Skin temperature	35.1 (0.02)	35.2 (0.01)	0.72 (0.37 – 0.87)	1.56 (0.96 to 2.37)
Electrodermal activity	2.83 (0.67)	1.91 (0.29)	0.80 (0.54 – 0.91)	1.25 (0.85 to 1.65)

SRM: standardized response mean; CI: confidence interval; Data are mean (standard deviation)

4. DISCUSSION

The current study investigated the test-retest reliability and responsiveness of Equivital Lifemonitor and photoplethysmography based wristwatch tools in assessing physiological parameters after the simulated fatigue task. Our results indicate good to excellent, and moderate to good test-retest reliability of the Equivital Lifemonitor and photoplethysmography based wristwatch in evaluating those parameters, respectively, to assess physiological measures. Additionally, the SRMs (>0.8) indicate that both tools could capture the changes in HR, HRV, respiratory rate, skin temperature, and electrodermal activity immediately after the 30-minute fatigue task.

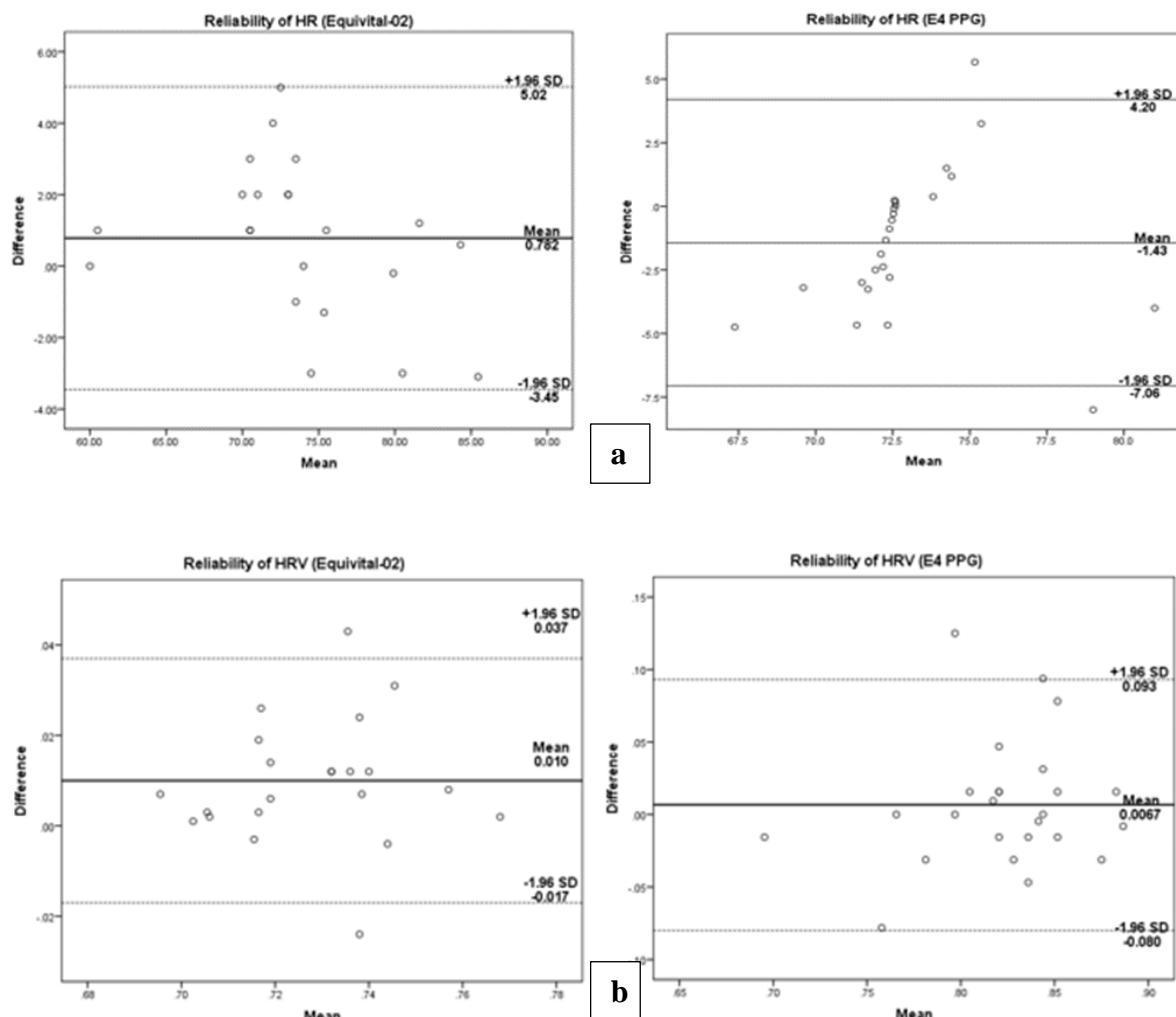


Figure 2. Test-retest reliability of Equivital Lifemonitor and photoplethysmography (PPG) based wristwatch in assessing (a) heart rate (HR) and (b) heart rate variability (HRV)

Our results supplement previous findings that indicate an excellent test-retest reliability of the Equivital Lifemonitor in assessing cardiorespiratory ($ICC > 0.95$) and thermoregulatory measures ($ICC, 0.97$) [21]. A previous study also indicated that the Equivital Lifemonitor could reliably assess HR and HRV. The Equivital Lifemonitor is easy to wear, while the wireless textile embedded sensors give comfort and make it suitable for real-time monitoring for a prolonged duration [34]. However, textile-based electrodes are vulnerable to movement artifacts because these electrodes do not have clips or adhesives [7,17].

Similar to the current findings, a previous study indicated an adequate test-retest accuracy of PPG based wristwatch in monitoring HR at construction sites [24]. They used mean-average-percentage-error and correlation coefficient to determine the accuracy of PPG-based HR monitoring. However, the current study used ICC to evaluate the test-retest reliability. Previous studies have considered ICC as a measure of repeatability over time because a reduced values of coefficients could easily indicates systematic errors in trials [35,36]. In use of this technique to determine test-retest reliability, the PPG-based wristwatch showed moderate to good ICCs for monitoring HR, HRV, skin temperature, and electrodermal activity.

This is the first study to use SRM to investigate the responsiveness of the Equivital Lifemonitor and PPG based wristwatch to monitor changes in physiological parameters after a simulated fatigue task. The SRM was calculated by dividing the score difference (posttest – baseline data) by the standard deviation of the group's score differences [37,38]. Both devices showed a large SRM (>0.8) which indicates their ability to capture the fatigue response by monitoring physiological parameters after a simulated fatigue task. Although the findings substantiate the use of these devices for fatigue monitoring, future studies are warranted to further validate these results.

The current study acknowledged some limitations. First, this study had a small sample size including only 10 participants, however, the large effect sizes for measuring physiological parameters after the simulated fatigue task suggests that both devices are useful in monitoring physiological parameters during construction tasks. Future field studies are required to investigate the reliability and responsiveness of these devices on a large sample of construction workers during actual tasks. Second, the current study did not report the validity of the two devices in measuring physiological parameters related to self-reported physical fatigue after construction task. Therefore, future studies should use gold standard measures of physical fatigue (e.g., blood lactate levels) to evaluate the correlations between the measured physiological parameters from these devices and the actual fatigue levels during construction tasks. Third, the current study only used one simulated construction task. Future research should use different tasks and different physical loadings to determine if these devices can reliably estimate physical fatigue during various construction tasks.

5. CONCLUSIONS

This study evaluated the test-retest reliability and responsiveness of Equivital Lifemonitor and PPG based wristwatch devices in assessing physiological parameters after a simulated fatigue task. Participants carried a wooden box of 15 kg for a given distance until they perceived physical exertion. The physiological parameters were measured with the Equivital Lifemonitor system and a PPG based wristwatch. These parameters were measured twice over 10 minutes of rest to determine the test-retest reliability and a third measurement was taken after the fatigue task to evaluate the responsiveness of two devices in assessing physical fatigue. The Equivital Lifemonitor and photoplethysmography based wristwatch devices are reliable in measuring physiological parameters after a fatigue task. Additionally, both devices can capture the fatigue response after a simulated fatigue task. Future field studies in a larger sample should investigate the sensitivity and validity of these tools in measuring physiological parameters for fatigue assessments at the construction sites.

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XI. SUSTAINABILITY CONSTRUCTION AND MANAGEMENT I (D2)

Assessment of Public Engagement Approach in Various Project Stages: The Case Study of Central Market, Hong Kong

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Abstract: The present research evaluates the public engagement approach in various project stages. Hong Kong had long been criticized as top-down and executive-led jurisdiction by overlooking the importance of cultural heritage and public concerns on public projects. It was suggested to the government to engage public and provide sufficient public consultation. Thereby, the government announced a series of revitalization and conversion measures in Policy Address in 2008. To carry out the measures, there were voices, because of diverse and sometimes conflicting interests, over the effect of revitalization project. On the other hand, studies reveal that there are benefits of revitalization and enhancement of public engagement approach. In pursuit of the subject, the present research aims at studying the Central Market as a case study pilot project. In October 2009, the Policy Address announced that the Central Market be revitalized. Tasked to implement the project, Urban Renewal Authority (URA) continued to adopt the people-oriented approach as the guiding principle in its core business and in heritage preservation and revitalization so as to create a sustainable development. Between government and the public, URA acts as a bridge for communication. As between URA and the public, URA conducted public consultation, set up an ad-hoc committee in January 2016 to be in charge of the project and will continuously inform the government and public with the updates and project progress. The main objectives of the present research are to assess the advantages and challenges in different stages of public engagement approach, to evaluate the engagement system, to give a comprehensive view for participation of stakeholders, and to find out effective strategies to enhance civil engagement. Research was achieved through interviews to key persons in the project, questionnaire that was distributed to community and experts in the field. Case Study of the Central Market was studied and investigated using different sources, such as newspapers, journals, etc, to evaluate the degree of public engagement in the project. Both detailed qualitative methodological approaches of interview, questionnaire, and case study, act as a synergy to demonstrate the research objectives and provide the comprehensive perceptions on the revitalization project. The results show that public participants in revitalized project have generated considerable value enhancements to social-cultural, environmental, political and economic aspect. This study provides valuable insights that the public participation can make positive contribution to sustainability in the city. The findings indicate that no any single system is flawless therefore seeking both public opinions and professional advices are also important as a comprehensive approach to achieve higher sustainability of the building.

Key words: revitalization, public engagement, public governance, sustainability

1. INTRODUCTION

In terms of urban planning and development projects, Hong Kong is characterized by top-down and executive-led government jurisdiction. Historically, as a British colony, the power of the Hong Kong government was greatly centralized, therefore the general public had little influence on decision making in government-led projects. Because of calling for democratization and decentralization in the 1990s, public have more opportunities for engagement. After handover of Hong Kong's sovereignty to China

in 1997, there was an increasing public interest in heritage conservation, different stakeholders including local residents, have been taken part in discussions and appeals for heritage conservation movements.

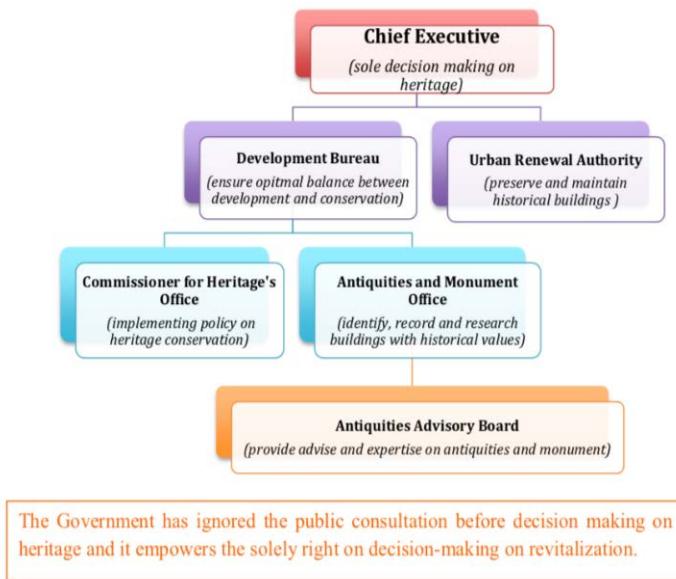


Figure 1 – Organization Chart for Heritage Conservation in Hong Kong

unattended to, it attracted tremendous attentions and provided insights into the major issues in public engagement in heritage conservation. The consensus among different stakeholders and public were built up through the series of elaborate public engagement exercise. The public aspirations on design and usage were adopted by URA. Although there have been many voices on enhancing public engagement, there are very few papers reinstating the significant role of public governance in revitalization projects. Public governance is the most essential drive to control time, budget, quality of projects and complies with existing statutory requirements. The research objectives are as follows:

1. To evaluate the degree of public engagement under current governance approach.
2. To examine the advantages and challenges stemmed from major social concern and social benefits to the neighborhood.
3. To assess whether the existing public engagement framework is comprehensive for local situation with a benchmark.
4. To recommend improvements on existing a public engagement framework for enhancement of public participation.

2. LITERATURE REVIEW

Hong Kong Government has long been criticized that there is not enough public engagement and only favors on the privileged groups on economic development [1]. Though the government has launched a series of conservation, conversion, revitalization and redevelopment measures in 2007 [2], the society are still questioning whether the measures can fulfill social benefit and whether the public projects have considered enough on social needs. In response to the social skepticism, the government has put a lot of resources on conducting public engagement to involve higher degree of public participation in public projects [3]. Since revitalization projects, which have been put forward in many districts are closely affecting the lifestyles and living quality of local communities, this paper is to rethink whether enhancing public engagement within the decision-making process for revitalization projects can help facilitate balance of interests under current governance approach. In below literature review, this is to study public governance model, the significance of public participation and the public engagement model.

2.1 Public Governance

Governance is related to the processes of interaction and decision-making among actors involved in collective problem, often in terms of ‘good governance’. Governance may take many forms, but the ultimate concept concerns ways of ‘creating the conditions for ordered rule and collective action’,

Following the guidelines set out in the Government's Urban Renewal Strategy, URA implements a “people first, district-based, public participatory” approach for its four core businesses i.e. redevelopment and rehabilitation, as well as heritage preservation and revitalization holistically, to create a sustainable and quality living in Hong Kong. URA acts as an interactive bridge between government and public in Hong Kong. To examine the public involvement in revitalization project, the Central Market, under supervision by URA, is chosen for study. It is a rare case that Central Market being in the prime commercial area in Central had been for so many years left dilapidated and

normally with reference to the activities and structures of governments [4]. A variety of entities can govern. The Human Development Report issued in 2002 claimed that “good” governance rid societies of corruption, give people the rights, and provide capacity to participate in the decisions-making on those policies affecting their daily lives [5]. “Good” governance generates rooms for sustaining the environment [6]. Others views good governance as participatory and transparent that foster long-term collaboration among public sector, voluntary and local concern group.

Beside the criticizing conventional governmental system which is top-down and closed decision-making process, there is increasingly focused on local and community governance modes which is horizontal, inclusive and participatory form of the governing process contributes to an ideal form of administrative process to foster local knowledge and action to be linked [7]. Collaborative governance involves the government, community and local individuals working together in a collective decision-making process focusing on the dynamic of network process (covers both the informal and formal relationships), governance structure, power balance, and effective communication modes [8].

Advocates of collaborative governance highlight better reciprocal understanding and expectation as well as multiple sectors voluntary participation [9]. Another benefit of collaborative governance is to provide a new participatory space for stakeholders to work together and agree on solutions in urban decision-making processes [10]. Collaborative governance can produce long-term agreements that resolve local conflicts and even generate social and relational outcomes via collectively seeking solutions to shared problems [11]. Furthermore, broad stakeholder participation and the quality of interactions among different parties can create unexpected process-based innovative alternatives [12]. Having said that, critics dominated by the regimes of powerful actors do not believe community-based approaches, such as ‘ideal-typical and normative prescriptions’ worked well [13]. Community based collaborative governance’s emphasis of a horizontal, network-based governance structure, while critics of the approach have emphasized the tendency for central government to exert a vertical, hierarchical influence as a hybrid nature of governance, or complex hybrid form of government/governance, where both horizontal networks and vertical modes co-exist [14].

2.2 Public Engagement / Participation

According to the International Association for Public Participation, public participation is defined as the involvement of those affected by a decision in the decision-making process with 5 stages in the planning of public engagement including: 1. Define initiative/project, goals, participants, timelines and resources / budget; 2. Determine level of public engagement and choose techniques through the worksheets; 3. Implement the public engagement; 4. Make recommendations and/or decisions and share results; and 5. Evaluate the public engagement process. With the term of Public participation in the 1992 Rio Declaration, Principle 10 of which refers to ‘the participation of all concerned citizens, at the relevant level’, coupled with ‘appropriate access to information’, states’ facilitation of ‘public awareness’ and ‘effective access to judicial and administrative proceedings’, it means that public participation is the vital part of sustainable development. Sustainability models are emerging with aspirations to the public participation for resolving the disagreements and conflicts between the government and public. So, community participation and satisfaction are extremely important for the revitalization project.

The relationship of Public Engagement and Governance are co-related, there are keep rising of concern by government on the issues of supporting and promoting high-quality, ongoing public participations [15]. And public participation is also a vital part in decision-making process and leadership is necessary for consistent and effective public participation activities. Several benefits generated from the public engagement campaign are as followings:

1. Significance of the decision making on the revitalization project: shifted from the importance of governance to local interest;
2. Support: transformed from Top minority (upper-middle-class) to a Bottom majority (grass-roots);
3. Changed the community interests: historic and architectural to the cultural and societal;
4. Increasing arguing from public perceptions at the development initial stage rather than through lobbying to reflect opinions from public on revitalization project, and better than evaluation by a designated expertise / professional.

In contrast, Beresford (2002) [16] notes two fundamental contradictions in public participation: enhanced political interest, but public dissatisfaction; official priority but very limited achievements and resourcing. Governments are investing considerable time and resources in the field of collaborative governance as it proliferates throughout many sectors. The increased public involvement that collaborative governance brings is often more costly than traditional forms of governance [17]. One study has shown that involving the public in science and decision-making costs about twice as much for a project than when the work is performed without public involvement [18]. And the outcomes of collaborative governance are still highly uncertain [19]. For these reasons, it is important that collaborative governance is only introduced and used when really warranted and various forms that it can take should be carefully designed.

2.3 Benchmark to Assess Public Engagement Mechanism

Yang (2005) [20] suggested that a comprehensive public engagement mechanism shall comprise the major criteria, including legitimacy, fairness, transparency and early involvement of public etc. to generate an effective communication and positive interaction for building trust between the government official and the public [20]. Alternatively, Yan (2017) [22] proposed that a sound mechanism is stemmed from the degree of public participation (e.g. from control taken by citizens, consult citizens to pacify the citizens etc.) which means he suggested a large degree of public involvement in the consultation system results to a higher effectiveness of public engagement [22]. Below is the comparison between two theories and to suggest the one which is fittest to be the benchmark for further assessment of case study in this paper.

Table 1 – Public Engagement Benchmark Comparison

	Yang's Theory (2005)	Yan's Theory (2017)
Rationale	Trust	People Involvement
Structure	A standardized framework	People-oriented framework
Approach	Mix with top-down and bottom up	Bottom up
Assessment Criteria	- Legitimacy - Transparency - Sufficiency of Time for public consultation - Fairness	- Openness - Degree of Participation (Passive Versus Active) - Level / Depth of Participation (Influence of participants)
Means of Participation	- Information gathering - Consultation (e.g. Survey, questionnaire etc.) - Feedback / Interaction (e.g. Public Forum/Workshop etc.) - Mediation of conflicts (e.g. Press launches / Meetings arranged by District Council etc.)	- Participation in Decision-making process (e.g. provide opinions in design brief and scope of works etc.) - Vote (e.g. public have the rights to agree and disagree the decisions)
Pros	- With a clear standard to design public engagement framework - To streamline the process of the public engagement mechanism → efficiency & a certain degree of effective obtained	- Emphasize on rights of democracy - Encourage people to express and public discussion - Higher acceptance by public due to rights of decision-making back to public
Cons	- Elitism / Professionalism may dominate the public majority as most power is still possessed by the authority	- Inefficiency / Ineffectiveness if no consensus be reached; - Policy failure if manipulation of politicians occurs

3. RESEARCH METHODOLOGY

The research methods adopted for the study being the combination of interview with URA Representatives, questionnaire with the target respondents comprised residents living or familiarized of

Central, as they are the most be affected the group and case study of Central Market. Figure 2 and table 2 show a clear research framework for this study.

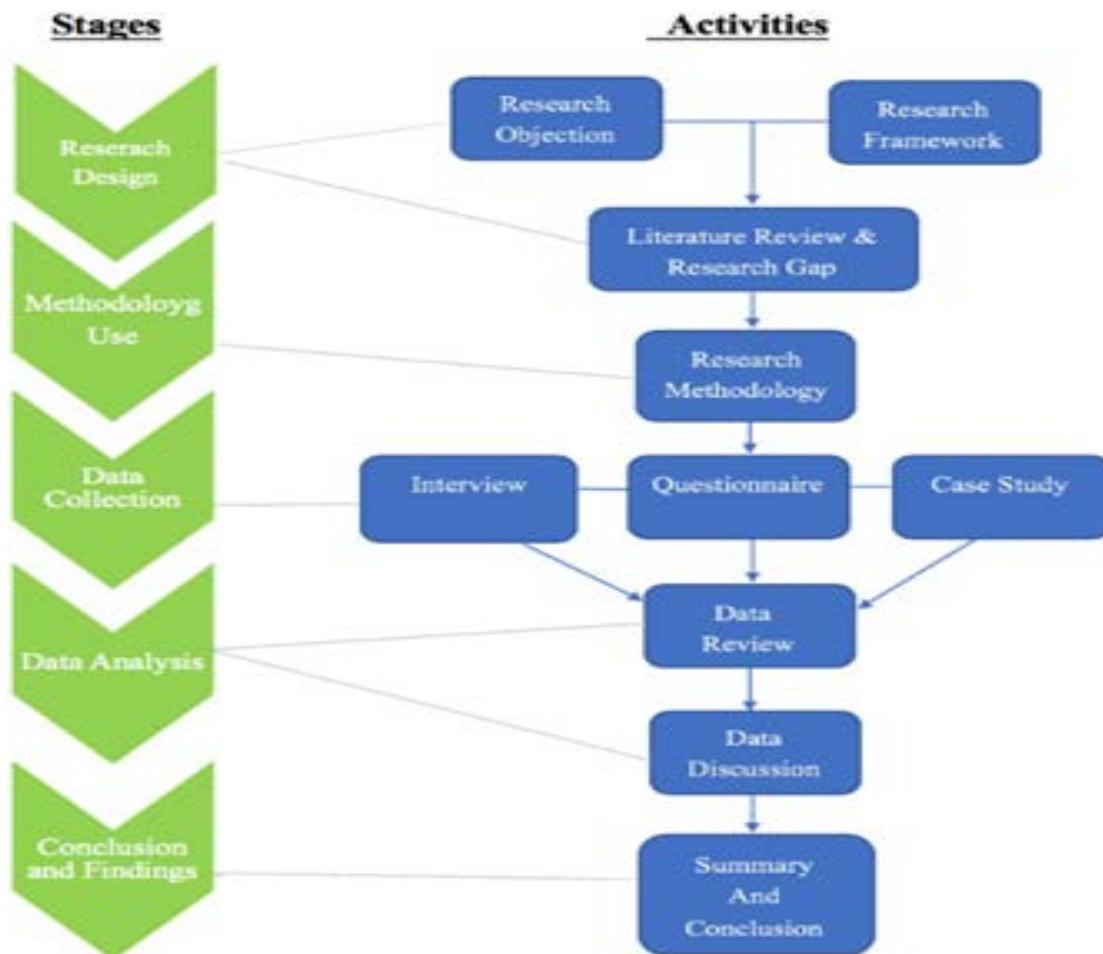


Figure 2 – Research Methodology

4. FINDING FROM INTERVIEW

4.1 Factors Contribute to Revitalization Decision Making

The AHP decomposes a complex multifaceted problem into a hierarchical structure consisting of the goal (at the top of the hierarchy) and criteria (at the bottom of the hierarchy). Based on literature review, 12 most significant factors affecting decision making of revitalization are identified and categorized under 4 main categories: economic, social-cultural, environmental and political as shown in Figure 3. Implementation of the AHP method in the revitalization project - Central Market by Urban Renewal Authority (URA) was carried out according to following procedure:

- Step1: Setting up hierarchy to break problem down into components and carried outbuilding
- Step 2: Pair-wise comparison matrix to compares the identified factors for establishing AHP structure
- Step 3: Assigning priorities ratio based on qualitative scale of 1-9 (higher value, greater importance)
- Step 4: Establishing priority vector to provide the relative weights for each factor on a scale out of 1.0
- Step 5: Logical consistency ratio helps to check the achieved results are acceptable ($\geq 10\%$)
- Step 6: Linearly combine the various priority matrices to achieve the final rank for each factor

4.2 Data Analysis

Data analysis showed that social-cultural aspect average weighted 0.325 (for the 5 respondents) is the most important among environmental, political and economic aspect, weighted 0.312, 0.312 and 0.052 respectively, consistency ratio is 0.1%, from the level 2 criterion. These results demonstrate that social-cultural factors such as social inclusiveness, cultural and heritage value is a prime aspect in

revitalization decision making. Calculated weight 0.490 showing that regulations is the highest priority in level 3 sub-criterion under economic aspect. Followings are economic viability ($w=0.449$) and economic viability ($w=0.062$), consistency ratio is 0.8%. This highlights the challenges of compliance to relevant regulations and the future economic viability and balancing the development cost. Weighted data showing that social inclusiveness (0.599) is the most important in level 3 sub-criterion under social-cultural aspect. Followings are cultural traditions ($w=0.219$) and economic viability ($w=0.183$), consistency ratio is 3.3%. Instead, social inclusiveness and cohesion is the major concern in revitalization decision making under social-cultural aspect. Reuse structural elements ($w=0.481$) is the highest priority factor in level 3 sub-criterion under environmental aspect. Followings are landfill waste ($w=0.452$) and recycling materials ($w=0.067$), consistency ratio is 0.4%. Considering the environmental aspect, people see the potential to conserve by reusing of structural elements. Lastly, data analysis showed that indication public involvement with the highest weight (0.447) is the most important among government policies ($w=0.436$) and stakeholders' interest ($w=0.117$) in level 3 sub-criterion under political aspect, consistency ratio is 0.1%. This indicates that the larger the extend of public involvement, the higher the satisfaction of the revitalization project.

Table 2 – Data collection methods

Data Type	Source	Description	Quantity / Data
Interview	Transcription from URA management interview	Semi-structured questions using AHP are asked to gain the first-hand information from the standpoint of URA for determining relationship of various factors relevant to governance, decision making	5 interviews
Questionnaire	Conduct street poll with designed questionnaire at various location near the vicinity	The data collected from surveys using AHP can help to examine the extend of public participatory	50 questionnaires
Case Study	Report, documentation and statistics data from meeting notes, journal and website etc.	Information gathered for public engagement benchmarks comparison and assessment	<u>Stage 1:</u> meeting notes <u>Stage 2:</u> Report for 6000 questionnaires, 2 charrettes <u>Stage 3:</u> Report for 4000 questionnaires, 1 public forum

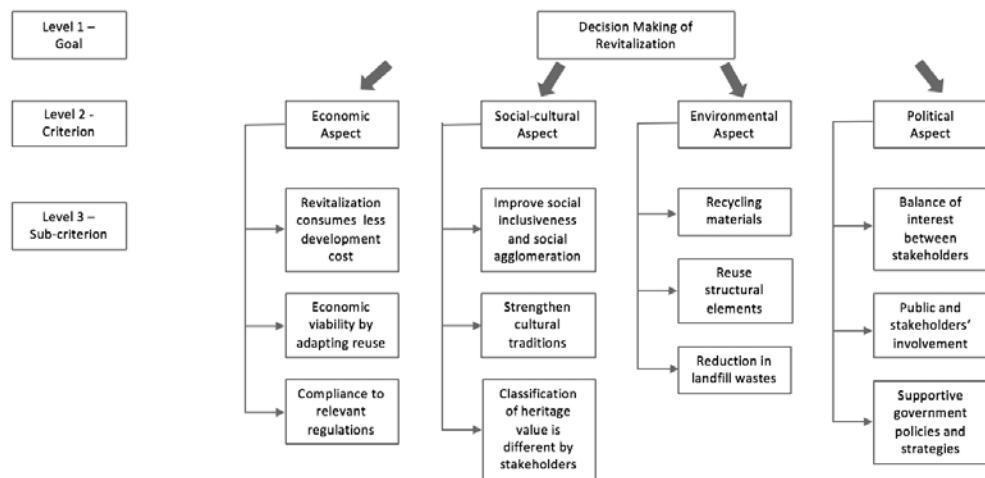


Figure 3 – Decision making factors of revitalization under governance approach

4.3 Discussion and Policy Implications

The combined results of interview in qualitative analysis (generated from part 1 & 2 of the interview question) and AHP analysis (generated from part 3 of the interview question) highlight the ways in which the factors related to community-initiation can contribute to revitalization decision making. As a result, several policy recommendations are made for revitalization in current governance approach. The social-cultural concerns the involvement of local community in revitalization project can strengthen their sense of belonging and allows them to express their idea regarding living environment therefore enhance social inclusiveness. This is a relative successful bottom-up model of revitalization. In regard to environmental aspect, the interview results show that government officers perceive positive impact on environment by reusing structural elements. The ultimate objective of any revitalization approach should maintain the integrity of the individual heritage building and preserve the original urban form and pattern of the surrounding area [23]. For political aspects, the decentralization of decision making can be achieved by launching policies to facilitate public involvement in revitalization. As a result, positive sense of belonging can be enriched. Regarding the economic, it concerns of compliance with existing regulations such as fire safety requirements would affect the ease of revitalization because of compressing cost and time engaged in obtaining building and planning approvals from relevant government departments.

5. FINDING FROM QUESTIONNAIRE SURVEY

5.1 Evaluate the degree of public engagement under current governance approach

Figure 4 shows the hierarchy display of level of public engagement by used analytical hierarchy process (AHP). It is also the quantify related factors for ranking based on their level of importance. There are included 5 criterions for the evaluation of level of public engagement under existing governance approaches: Inform, Consult, Involve, Collaborate and Empower. Sub-criterions are developed to show the items that need to elaborate of those 5 criterions.

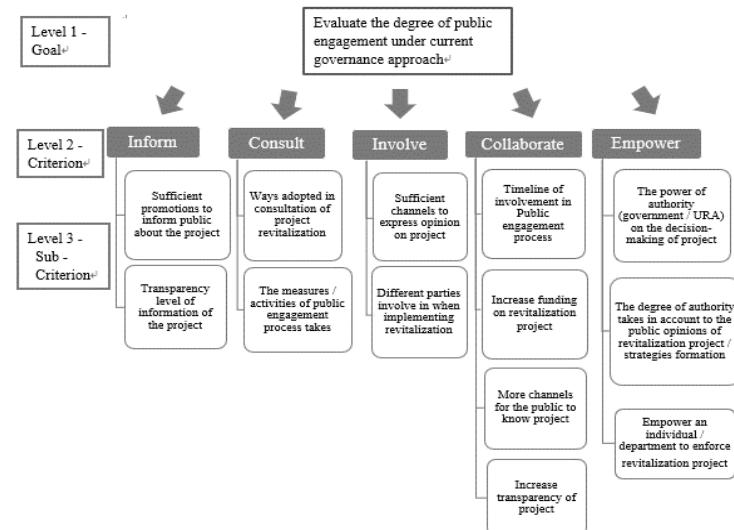


Figure 4 – Evaluate the degree of public engagement under governance approach

5.2 Data Analysis

Part I: Background information and Personal details

The age group of majority interviewees are between 30 – 39, and most of them are living or working within the district are around 3 – 8 years. Around 90% of interviewees know that what revitalization project is but they do not express their views on the revitalization projects before. Nearly all of them understand that Central Market is under revitalizing, but some of them do not know the progress of revitalization work.

Part II: Knowledge on Revitalization Project of Central Market

Most of interviewees know about the Central Market but they have limited knowledge of the revitalization project of Central Market, also not much of them have been visited it before. Only 1 interviewee expressed his/her view on the revitalization project of Central Market, the others are mentioned that they have no idea / not interested on it. It showed that Government and URA did not promote the message of revitalization of Central Market much at the initial stage of consultation process.

About 60% of interviewees do not have any idea of the parties who has overseen the revitalization project of Central Market. And followed by it, about 16% of interviewees selected URA that has the sole power to oversee revitalization project of Central Market. More than 80% of interviewees stated that they knew the project through media / News, then followed by through Peer / Forums / Facebook and Government Gazettes / Websites. About 42% of them stated that they can express their views on the project through media, and only 28% of them mentioned that they can express opinions through Government websites. People considered that they can only express their views through unofficial channels mainly like media rather than official website set up by government / execution parties. Moreover, the data collected which show that the revitalization project is not so attractive to the people who working / living nearby to visit. It seems that the promotion works of the message of revitalization of Central Market to public are not enough.

Part III: Opinions on Revitalization Project and Public Engagement Process

Most of interviewees selected that Government / execution parties should be established more channels for public to know about the project, also followed by increase the funding and transparency of the project, those 3 elements can help to improve the effectiveness and efficiency of project. Moreover, majority of interviewees selected that benefits to the community and public recognition as the most important factors when considering revitalization project of Central Market, then followed by the revitalization feasibility and public recognition. Those factors are crucial to lead the project being execute successfully. In addition, most of interviewees will decide to express their views under the situation which related to their own interests and think that Government / execution parties should establish more open and public ways such as street polling for the public to express their views on the project.

Part IV: To examine the degree of satisfaction of public participation, sufficient channels to express views and level of transparency of information on revitalizing project of Central Market under Governance approach

It mainly shows that interviewees rated the part of consult then followed by involvement in the public publication process are the most important criteria compared with others. Also, it shows that the similar level of importance of information transparency and sufficient channels of the project to the public to know about it, with the equal importance level between the sub-criteria of sufficient channels to express opinion on project and different parties involve in when implementing revitalization. Meanwhile, interviewees rated the measures / activities of public engagement process take that is a moderate importance of factor adopted in consultation of project revitalization. Finally, although the power of authority (Government / URA) on the decision-making of project are override others sub-criteria and parties, interviewees also rated a certain level of the importance level that the execution parties need to take in account of the public's opinion towards revitalization project / strategies formation throughout the whole process and empower an individual / department to enforce revitalization project. For overall comment on the project, people stand moderate on the performance of revitalization project which implemented execution parties.

6. CASE STUDY: ASSESSMENT OF PUBLIC ENGAGEMENT MECHANISM

Case Study Research is conducted to assess if URA's mechanism is comprehensive for absorbing public opinions. First, the criterion for benchmarking have been developed (see Figure 5); Second, a case study will focus on URA public engagement report published by URA - "Urban Floating Oasis: Public Engagement" in 2013 and "The Central Oasis- Design Concept Roving Exhibition" report in 2011 and its result report of Central Market questionnaire surveys [24]; Third, URA's approach and process public engagement will be evaluated and analyzed if it can fulfill the criterion.

6.1 Data Collection

Public Opinion Survey in 2010 & 2011 - The public engagement programme started with Public Opinion Surveys conducted by AC Nielsen on 2010 and 2011 [24]. The opinions and results were generated by conducting street poll that focused on uses and general concepts and mainstream direction of building design. Design Concept Roving Exhibition - According to the Central Oasis: Design Concept Roving Exhibition Report published by URA in 2011, since the Central Market Revitalization Project

was announced in 2009, the Community Advisory Committee had received the public opinions on future use of the building and their expectation [25].

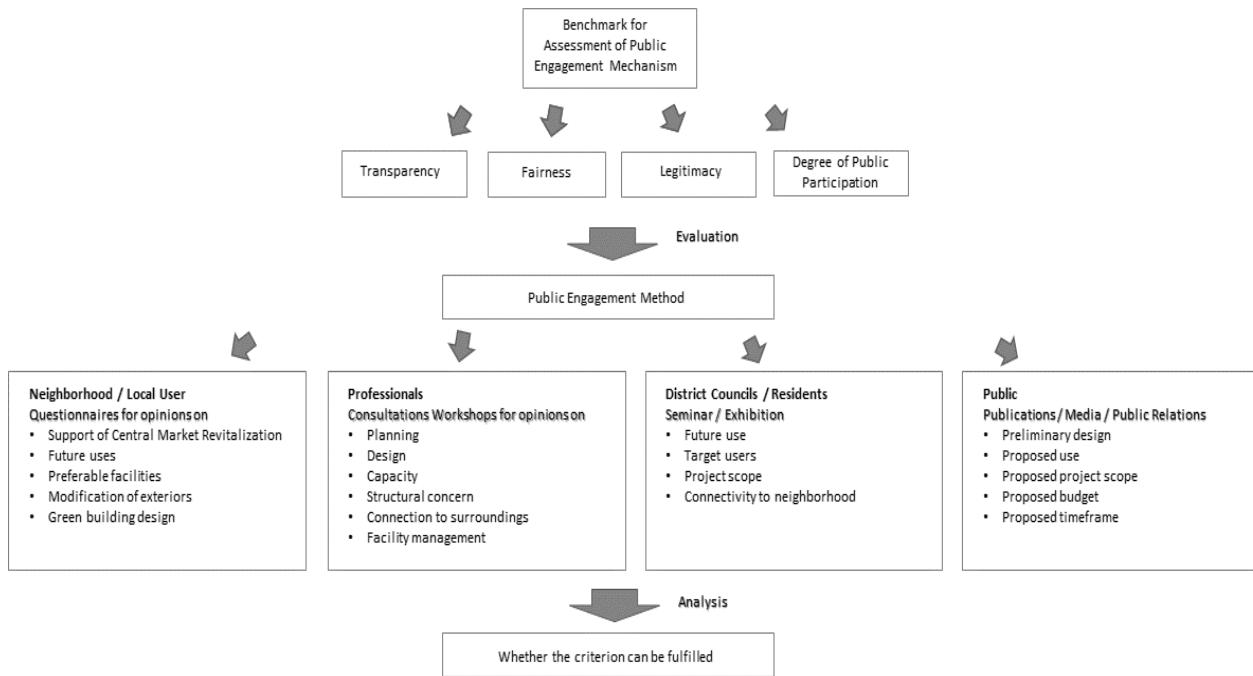


Figure 5 – Work Flow for Case Study Research of the Public Engagement Process

6.2 Data Analysis

As shown in Figure 6, the above is a flow chart to explain the consultation process of stage 1 – 3 URA's public engagement process. This paper is to analyzed whether URA's public consultation process could achieve a comprehensive approach:-

Public engagement methods that incorporated public views in the scope defining via open and fair consultation strategies, including absorption of public views, workshops for brainstorming, publications of public media for interaction of the authority and public in order to meet the above criterion. In that, it enables absorption of public voices as public participation; the project information, process and result of public consultation etc. were released to public to achieve transparency; After the absorption of public view, URA has attempted to generate / consider feasible public opinions into the project design direction, so that the general public can feel being respect, in order to achieve legitimacy; And, the consultation process is open for all and public have equal right to participate, so as to achieve fairness. The survey shows that community satisfaction in revitalization is very important for the revitalization project. The process and result of surveys achieved a high degree of transparency for revealing the details to public. Others criterion were principally fulfilled. It is advisable that URA surveys could absorb more public views on design intent, e.g. taking the example of Kai Tai Fantasy Competition held by the Development Bureau and Energizing Kowloon East Office (EKEO) for Kai Tai development [26], URA could hold a public design competition (subject to time and budget consideration etc.) to allow more public input. The exhibition helped absorption of public views and professional opinions. Most criterion were principally achieved and encouraged participants. URA studied the feasibility and generated the practical alternatives under a practicable solution to strike a balance between construction cost and social benefit, so as to maximize public interests. Under the analysis of the benchmark, URA's public engagement was able to achieve the criterion in an efficient approach as analyzed in the above. To achieve a comprehensive approach, it is advisable that URA may arrange public design competition to consolidate public input in design intent, subject to time and budget consideration. Also, URA is able to maintain collecting public views which can fulfill the criterion while ensuring public authority / professionalism to take lead in the project.

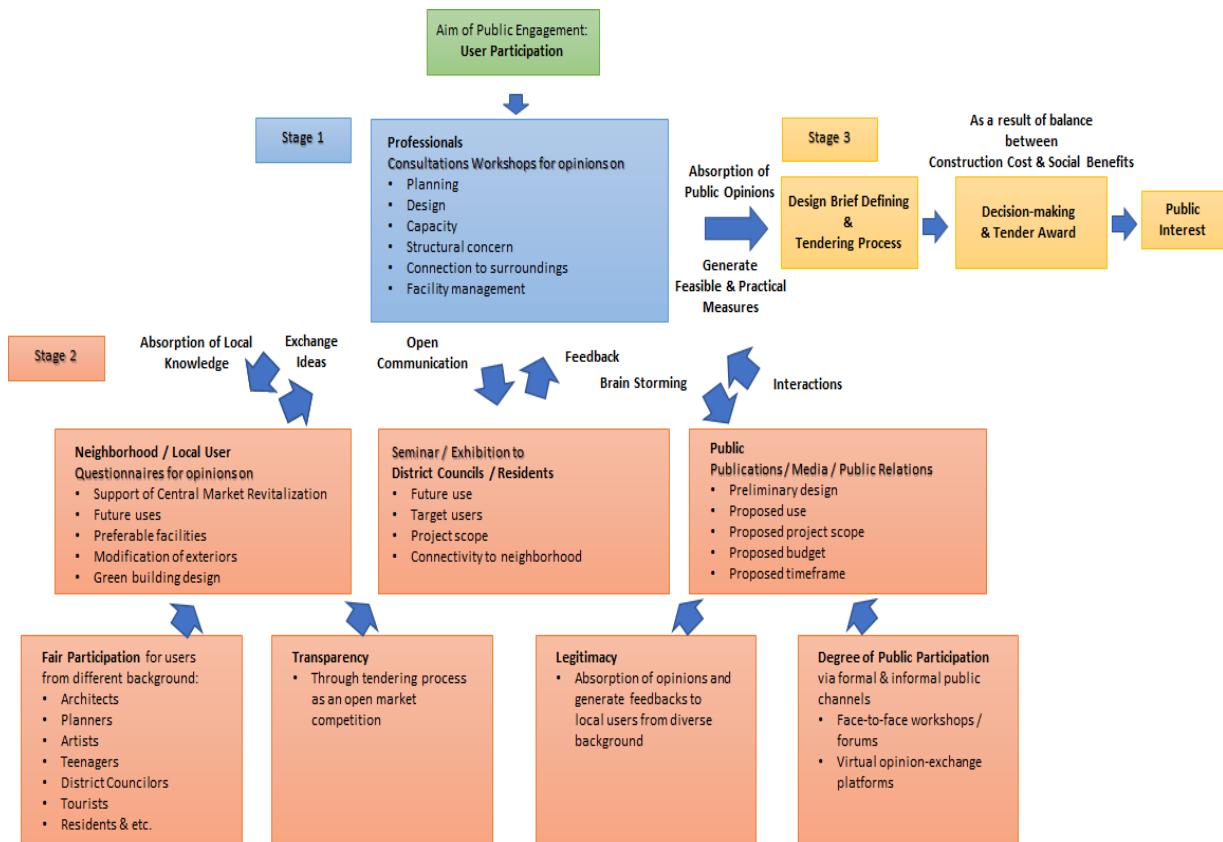


Figure 6 – The Public Engagement Approach to Carry Out Public Consultation

7. CONCLUSION

The interaction of governance and public engagement is important to public revitalization project. Public participation should be engaged in decision-making and considers social benefits. It can also help public to better understand the project requires to fulfil social expectation, practicability and the compliance of statutory requirements [27]. To balance diverse groups from conflicting interests, decision-makers shall define stakeholder's interests and concern, then to formulate the best suit public engagement mechanism for the project implementation and provide adequate publications and measures on public relations strategies to explain their decisions to stakeholders that how social values and concerns are being absorbed. This is to convince the society and liaise supports from the public. Under the current governance approach, the revitalization of Central Market has involved sufficient of public participation overall. This paper recommends the officials to arrange strategies on public relations and social liaison teams to increase mutual trust between the government and the public.

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Benefits and Challenges of Modular Integrated Construction in Hong Kong: A Literature Review.

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Abstract

Modular Integrated Construction (MiC) has gained quite momentum as it provides solutions for several problems in the construction sector, particularly in Hong Kong. MiC is converting the building into modules and erecting them easily on site providing various benefits, such as cost and time savings, better quality, lower risk, higher sustainability, less injuries and accidents, etc. The MiC is considered the best alternative to traditional construction approaches in solving the huge housing demand problem in many cities all over the world due to the time-saving privilege. The utilization of MiC is facing a lot of challenges, which are considered obstacles to the wide acceptance of this technique in the construction industry in Hong Kong. This, in turn, has led the interests of the research community to investigate its benefits and challenges aiming at addressing several solutions to harness the benefits of this technique and to tackle these challenges. The present research aims to review the main concept of MiC and to determine the benefits and the challenges of implementing MiC in construction industry. The findings of this research highlight the advantages and limitations of incorporating MiC technique in Hong Kong, which will help the stakeholders to effectively utilize this technique in the construction industry.

Keywords: Modular Integrated Construction (MiC), benefits and challenges.

1. INTRODUCTION

Prefabrication, the umbrella under which Modular Integrated Construction (MiC) takes place, is not a new invention; it goes back to the 17th century [1] where houses were built in England and shipped all the way through the Atlantic Ocean to a village named “Cape Ann” back then. England was clearly a hub for prefabrication at those ages. In 1790, simple shelters were sent to settlements in Australia in order to be used as hospitals, cottages and storages. Similar structures were noticed in Africa, particularly in Sierra Leone and South Africa. Despite the aforesaid structures were not completely prefabricated, it provided a noticeable reduction in the labor force required [1].

In the year 1830, the Manning Colonies in Australia developed a new system as an improvement for the original one. In 1833, the light balloon frame system appeared in the United States, particularly in

Chicago but such system had a problem that it caught fire too quickly which led to the disastrous Chicago fire. Taylor [2] discussed the development of prefabrication starting in 1830 at Manning's portable colonial cottage to 1890 where standard cast iron catalogues were used at Macfarlane's Saracen Foundry in Glasgow, and how the architecture evolved from ad hoc buildings to planned production.

In 1851, a unique building named "Crystal Palace" was designed and built using the prefabrication technique, the materials used were iron, wood and glass. This building was designed by Sir Joseph Paxton in less than two weeks and constructed in only few months, the building was presented in Britain's Great Exhibition during that year. Another unique building was built in the United States, in the 1930s, named Aladdin and known for its' erection just in one day, the new design was promoted due its low cost per foot and high utilization of timber lengths. In 1932, George Fred Keck utilized the metal sandwich panel wall system to build "House of Tomorrow" and "Crystal House", and present them in Chicago World's Fair in 1933. The idea was implemented in the single-family homes in the United States, as they were built as module on a chassis in manufacturing facilities, this technique idea compromised 25% of this type of houses between years 1954 to 1968 [1].

Another famous building, the Hilton Palacio Del Rio Hotel in San Antonio, Texas is considered a prefabrication landmark as it was finalized from design to occupation in just 202 working days, the hotel consists of 21 stories, the first four stories were constructed using conventional technique, while the remaining stories, which were 496 prefabricated modules, were erected in 46 days [1]. According to [2], the utilization of off-site construction or prefabrication increased after World War II (WWII) as it provided a solution for the increasing demand of housing and provided a more dynamic solution compared to the traditional method. In the 90s, the world started adopting MiC in several functions such as hotels, prisons and houses. The 90s were evolutionary days for MiC, in 1999, the research community started discussing the financial benefits of automation and mechanization in construction.

From the 17th till the 21st century, prefabrication existed in the construction sector in various ways; it was adopted for its speed of erection and to cover the demand for housing after wars, like what happened after WWII. The widespread usage of prefabrication occurred starting from the beginning of the 21st century and MiC started to gain momentum in the last two decades, therefore, this research aims at reviewing the main features of MiC. First, a brief introduction will be provided to figure out the differences between various expressions used in this area. Second, the benefits of MiC will be discussed. Third, the challenges of MiC are going to be presented. Finally, we will present how MiC progressed in Hong Kong and what we concluded from our research.

2. DEFINITIONS

Prefabrication, hybrid systems, panelized system, modular construction technique, industrialized building system, pre-assembly, off-site construction and many other expressions can be found when researching about prefabrication and modular integrated construction; what really matters is the meaning of each expression and how the construction sector views each expression. Table (1) provides definition for these expressions. From Table 1, it can be concluded that prefabrication, industrialization, and off-site construction give the same indication when used or the same construction concept, all of them are referring to using manufacturing facilities away from site to construct building components then transport them back to site for installation. On the other hand, preassembly is another process which is concerned with putting together various components during manufacturing in order to reduce the amount of work on site. In general, building construction can be done using one or various types of prefabricated elements (i.e. hybrid systems). These elements can be 2D elements (i.e. panelized elements such as walls, floors, roofs, and columns) or/and 3D fully furnished modules that contains everything needed.

3. BENEFITS OF MiC

In this section we are going to demonstrate how MiC can enhance the construction sector of any given market and how various researchers were able to analyze and track the benefit of MiC and come up with facts and conclusions. Figure 1 represents the number of papers in each construction market that have previously discussed MiC and prefabrication. While, figure 2 represents how many references support each benefit of MiC benefits; which can be considered as an indicator for how common such benefits can be achieved and reflect a common agreement on certain benefits among the research community worldwide.

Table 1. Definitions of Scientific Expressions

Expression	Reference	Definition
Prefabrication	[2, 3]	“Prefabrication” which consists of two parts; the first is “Pre” which means something that was previously prepared or made and the second part is “fabrication” which indicates the manufacturing process itself and accordingly the word when utilized in a construction setting such as prefabricated buildings it shall mean buildings that were already manufactured.
Industrialization	[4-7]	A term used when relying on factories/manufacturing facilities to build parts of a building or the whole building, similar to prefabrication, and it is commonly used in Malaysia
Off-Site Construction	[2, 3]	Performing activities away from the construction site itself, which is the core concept of prefabrication as an idea, in order to enhance quality and save time, building components are manufactured in off-site facilities and then transported to site for installation/erection.
Preassembly	[2, 3]	Process which is concerned with putting together various components during manufacturing in order to reduce the amount of work on site
Modular construction	[1, 4, 6]	Modular Buildings or Modular structures that are built using the MiC technology which is the manufacturing of 3D fully furnished modules that are volumetric and box like that contains everything needed. This type offers very limited site operations which decreases the time of construction.
Panelised construction	[1, 4]	A system in which buildings that are manufactured from 2D elements which constitute walls, floors, roofs and columns. Ex: A famous hotel in China named Dongting Lake.
Hybrid construction	[1, 4]	It is a combination between Modular and Panelized systems, a famous example for it is the Meridian First Light House in New Zealand.

3.1. Time

MiC technology offers a benefit of time saving because it allows rapid construction. Simply, modules are brought to site then erected, and it overlaps the work on site with the work in the manufacturing facility [4, 8, 9]. Furthermore, MiC can eliminate almost 80% of the construction site activities hence, eliminating a huge amount of delay due to resource management and weather problems [4, 10]. Using the manufacturing facilities provides a smooth flow of activities in a linear way for repetitive work, even better than performing linear activities on site. The use of machines and automation technologies also helps in enhancing this process and in decreasing the time. In addition, it helped solve the skilled labor shortage problem occurring in countries like Malaysia [11]. Navaratnam, et al. [10] believes that due to better delivery arrangements of materials to the manufacturing facilities and due to the eliminated delays of weather conditions and disruptions, the time saving achieved when using MiC can reach 40%

compared to traditional/conventional construction methods, which means early operation of the project and accordingly a decrease in interest payments for capitals [12].

3.2. Risks, Health and Safety

MiC moves almost 90% of the construction activity to manufacturing facilities which eliminates a lot of risks like; weather condition, disruptions, equipment problems, labor low productivity and other sorts of risks that would make the project suffer more delay and incur extra costs [9, 12, 13]. The reduction in on site activities makes the site tidier [11] and decreases the occurrence of accidents among labors which enhances the construction industry and makes it safer [9, 11-13]. Kamali and Hewage [14] mentioned that when using MiC reportable accidents was reduced by 80% compared to conventional methods. In addition, the reduction in usage of equipment, mainly in MiC we use lifting equipment only, the risk of damage to private properties due to the presence of huge amount of large equipment decreases.

3.3. Cost

In general, the benefits of MiC from the cost point of view can be concluded easily. First, time is money [14] so as project duration is reduced the time-dependent costs are reduced such as crane renting cost [10, 11, 14]. Second, the site preparation and mobilization for MiC projects are much simpler, leading to a reduction in costs [12, 14, 15]. Third, the percentage of rework compared to the conventional methods would decrease to only 10 to 20% as a consequence of minimal on site activities, resulting in cost reduction for owners and less risk of budget overruns for contractors [9, 16]. Furthermore, during the bidding stage, a contractor will evaluate the risks of MiC to be lower than the traditional methods, as these methods include higher health and safety precautions [13], bigger exposure for adverse weather conditions [13], bigger risk of poor workmanship from labors resulting in more rework and finally, risk for damage to property is much higher [14]. This will reduce the risk percentage the contractor is taking into account during bidding stage.

In addition, it is standard procedure in projects that the contractor insures the project with various types of insurance policies as per the contract conditions. When using MiC, the feature of the project is different, it is much safer now which can lead to reduction in cost of insurance policies' premium. Furthermore, from the owner's perspective, the project shall not suffer from variation orders like the traditional ones, the MiC technique obliges all parties to a certain time after which no changes are allowed which leads to much lesser variation orders or no variation orders. By numbers, Kamali and Hewage [14] and Hong, et al. [17] stated that cost reduction in capitals when using modular construction can reach 10% while, Navaratnam, et al. [10] and Kamali and Hewage [14] discussed the benefit of lower material prices due to bulk orders when using MiC. Kamali and Hewage [14] mentioned that MiC reduces the labor cost by 25% compared with the traditional method.

3.4. Sustainability

Prefabrication or Off-site construction (OSC) helps in decreasing the wastage of material and provide cleaner environment [5, 9-14, 18]. Navaratnam, et al. [10] stated that OSC has great environmental positive impact from noise reduction and decrease in disruption by 30 to 50%. In addition, OSC buildings are known to promote recycling specially when using steel structure modules, Kamali and Hewage [14] reported that 76% of researchers confirmed the ability of MiC system to reduce construction wastage. Marjaba and Chidiac [18] stated that OSC, which ranges from prefabrication of cladding to prefabrication of complete modules, offers less wastage in material, reduction in environmental impacts compared to conventional method, and ability to build according to higher specification if needed. Furthermore, OSC allows the application of lean production principles which improves sustainability. In fact, OSC would result in wastage less than 5% [18], and it would also decrease the carbon emissions resulting from transportation due to the reduction of transportation required, particularly in MiC [14, 18]. In general, MiC provides positive impacts on the three aspects of sustainability; environmental, social and economic.

3.5. Quality

Quality enhancement is one of the most guaranteed benefits of MiC, the manufacturing facilities provide adequate fabrication [5, 8, 12] for all components in a better work environment with more advanced production lines, machines and automation technologies. The precision available in factories reflects in higher quality, better efficiency and easier application of higher specifications or standards [5, 9, 13]. The application of quality control (QC), quality assurance (QA) and total quality management (TQM) in manufacturing facilities is much better [8] and effective compared to its application on site, which paves the way to the application of lean production /Construction. The off-site production process allows close monitoring by multiple specialized persons and shall result in better quality for products [5, 10, 11, 13]. Kamali and Hewage [14] demonstrated two further benefits for MiC, first, the workers will have better learning curves when working in factories compared to site activities because of small tasks assigned to each worker which promotes “work specialization”. Second, all of the material will be away from severe or harsh weather conditions, thus, the final products will have high quality building finishes.

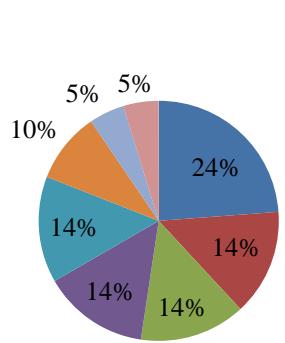


Figure 1. Various markets of previous studies.

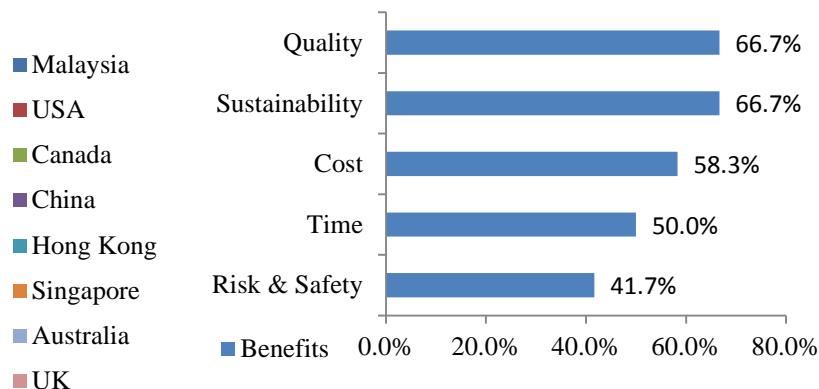


Figure 2. No. of papers mentioning each benefit

4. Challenges of MiC

Albeit the benefits of MiC, its’ spreading in various construction markets lagged in the last decade, and Hong Kong city is a clear example for that. The reason behind this problem is that there are challenges crippling MiC from spreading. In this section, we focus the light on the details of these challenges. Figure 2 represents the number of references mentioning each challenge facing MiC, the numbers can be indicative of how common problems are occurring in various countries and markets.

4.1. Initial Investment Cost

Chai, et al. [4] stated that the application of MiC requires a large amount of initial investment cost to cover the expenses of the plant, machinery, moulds, formwork and suitable transportation arrangements. This, in turn, requires that the demand on such new business is good enough to make it feasible economically [9, 11, 14, 19]. Molavi and Barral [8] and Navaratnam, et al. [10] believed that the costs of design and engineering will increase when using MiC, in addition, MiC structures require more materials to sustain a safe structural system [8], which adds extra costs. Furthermore, the shortage of specialized contractors may lead to additional costs due to scarcity of required experience. Haron, et al. [12] stated that the high capital investments and high interest rates used when using MiC are not justified in the competition with traditional methods that offers lesser investment costs. Zhang, et al. [20] studied the barriers affecting the prefabricated housing in china and provided an order of importance for all these barriers from most important to least important, the result of this study concluded that the high initial cost

barrier is the most crucial barrier holding the wider spread of MiC in the residential housing industry.

From the financing point of view, Velamati [21] believes that the financial sector is still familiarizing itself with the concepts of MiC and how it works. Lenders are still very cautious when dealing with MiC projects and they are more concerned about the completion of the project. This problem is occurring due to the scarcity of firms specialized in fabricating modules, so the lenders believe it is risky to fund these projects because if the modules manufacturer goes bankrupt they may lose their money. In other words, they believe that the risk of losing their money is high, consequently, they demand more guarantees which limits the fund. Hwang, et al. [19] studied the constraints facing MiC and how to mitigate them, the initial cost problem was ranked 5th according to his statistical study and the possible mitigation for it, are to implement feasibility studies, to develop software/systems that perform economic studies and to use BIM technologies.

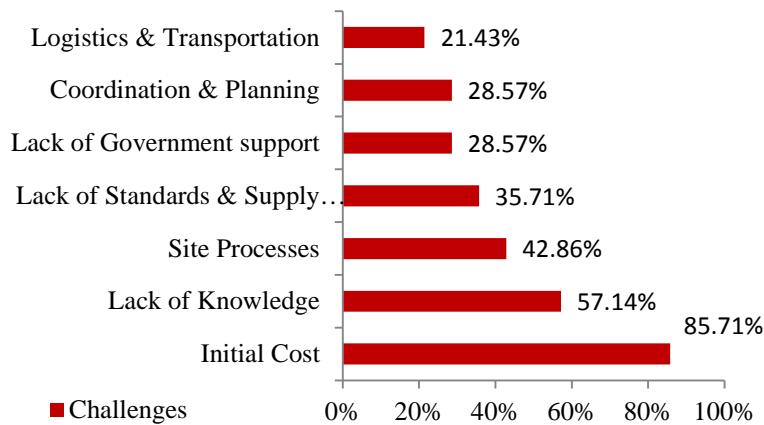


Figure 3. No. of papers mentioning each challenge

Schoenborn [13] mentioned the cost problems facing MiC and believed that the industry should push towards complete mechanizing of the manufacturing process, eliminate on site work and maximize the usage of recycled material in order to make MiC more cost effective. Rahman [22] believes that the need to purchase all the materials at the beginning of the project is burdening MiC and believes that if the demand is fluctuating this can lead to cost increase that would make MiC less cost effective compared to traditional methods. This study concluded similar results and ranked the high initial cost problem 2nd among other barriers identified in UK and China.

4.2. Logistics and Transportation

Each project has its own unique location and feature, and this will result in facing different traffic regulation and transportation regulation. Over populated areas will hinder the movement of modules or even restrict it, some roads may not be primarily designed to carry the load of the modules [14, 19, 22]. On the other hand, some module manufacturers allow maximum transportation distance in order to maintain the wellbeing of the module itself from damage [14]. In case of transporting to distant locations, the cost of this process must be studied well and the proper permits should be issued in order to prevent any delay that would negatively influence the benefits of MiC [14]. Shipping is another deal; it will require various procedure and regulations to prevent any damage to the modules and make sure all of them arrive to site with no damage. In addition, this whole process will have its restrictions in terms of size, weight and dimensions of the modules [14]. Rahman [22] ranked the transportation issue the 7th among other barriers in his study on UK and China, while Hwang, et al. [19] ranked the transportation problems the 8th among several constraints being studied and they suggested that the manufacturing facility should be placed close to the site to minimize the transportation costs and problems.

4.3. Coordination, communication and planning

The fragmented nature of MiC and the diverse nature of its stakeholders require an immense amount of coordination and planning in order to avoid technical and cost overrun problems [9, 12] as the design of MiC project is different from the conventional design. The modules itself require extra work to be accurately designed and fit for its purpose. Furthermore, a clear scope must be defined from the beginning in order to avoid any changes later on as changes are very hard or even impossible during the construction stage of the project. Detailed plan with a clear scope should be present as early as possible [14], in order to enhance the coordination and communication. Planning between the manufacturing facility and the site management is crucial in MiC, idle expensive equipment or large stock of modules on site can complicate the cost status of the project leaving all parties with losses and delays. For better control of the process it is recommended that the main contractor charges the responsibility of elements assembly on site and subcontracts the manufacturing facility work in order to have the upper hand in planning and coordination of the flow of work [21]. Furthermore, when using MiC in residential high rise buildings, the owner would require to occupy multiple stories while the project is not yet finished, others would rather occupy the building after all the on site activities are finalized. This process must be well planned and communicated among project parties in order to avoid any losses to any party [21]. As a solution, BIM can be a useful tool to enhance coordination, communication and planning between all stakeholders.

4.4. Lack of awareness and knowledge

Lack of knowledge about MiC leads to various complications for all participants, some of them fail to do their part effectively due to this problem while others provide poor quality outputs for the same reason [11, 12]. The problem gets even more inflated when owners are not aware of what MiC is and how it works so they tend to avoid it or sometimes neglect its benefits [14, 19]. In other cases, they know the benefits but lack the knowledge, so the process is not done correctly and therefore, they lose the benefits of MiC, mainly time and cost reduction. Similar concept was discussed by Navaratnam, et al. [10] who concluded that the knowledge of MiC needs proper communication and enhancement in order to allow for better implementation. Furthermore, the educational sector should step in and support spreading the knowledge and awareness related to MiC. In the same context, engineers being unaware of the essential elements for designing MiC building [9] decreases the probability of harvesting the MiC benefits. What makes things worse is the lack of research and development (knowledge) that identify the proper ways of implementing MiC. Another factor that contributes to the problem is the lack of awareness from the end users/ occupants/clients [14] which may affect the sales/rentals of the project and affect the cash flow of the employer. Furthermore, lack of awareness formed a suspicious attitude towards the performance and quality of MiC and a wrong belief that MiC buildings are of low quality due to its light weight [22].

4.5. Site processes

Site conditions in MiC may be simpler than traditional site conditions but it has additional requirements to fulfill its purpose correctly, such as additional space to be used for storage, mobilization and proper circulation for equipment. Thus, constituting a constrain in applying MiC. In addition, installation of modules requires advanced equipment and skilled labor which burdens the process even more [11]. Various literature mentioned that the lack of skilled labor forms a major problem and a challenge in spreading MiC [4, 9, 12, 14, 20].

4.6. Lack of codes, standards, standardization and supply Chain

Standardization is important for the stability of any industry; this can allow MiC to gain edge over other methods of construction. Component standardization is reported in the literature as a key factor affecting MiC [11, 12, 22]. The concept is to help decrease initial costs of design and mouldings. Furthermore, it is

thought that standardization would be critical to the idea of reuse [23], and this shall help MiC become more sustainable by decreasing its life cycle wastage. In contrary, the lack of standardization is believed to cause wastage in materials and additional costs [12]. A study carried out in China by Zhang, et al. [20], ranked the challenges facing prefabrication in general and it ranked the lack of supply chain as the 4th most important challenge and lack of standardization as the 5th most important. The supply chain problem is due to the fact that the industry is fragmented and consisting of various types of trades [20, 22] and, it makes it hard to realize which components are available locally and which are not, making the planning and design stages even more complex and putting the project at risk of delays. MiC in each country, and in China specifically, needs more standardization, serialization, and scaling to establish the required supply chain of components and trades that shall promote MiC [20].

Lack of technical standards formulates a main barrier facing MiC and stopping it from spreading, some volumetric parts in projects were customized only for such projects and became one of its kind. These types of practices force redesigning every time and increases material waste. A solid reliable base must be established so that all parties can refer to during their work [20].

4.7. Lack of incentive and government support

Despite the numerous benefits of MiC, adopting MiC concept in the construction industry is slightly growing. One of the main reasons for this situation is the lack of support the governments are showing, and how they failed to provide enough incentives for owners/employers/investors to adopt MiC in their projects [12, 20]. Zhang, et al. [20], mentioned that there is insufficiency of promotive and incentive actions that would promote MiC. In addition, possible policies and facilitating regulatory mechanisms are not provided. In fact, it's part of the governments' roles as the mentor, supervisor and facilitator of the whole system to make sure that if new technologies are beneficial, they are well promoted among consumers. The situation may even get worse without the required incentives and promotions, the public perception of MiC is defensive, and they believe that MiC technique provides projects with lower quality. In addition, other companies have certain mindsets and they don't want to try anything new, this type of thinking is reluctant to innovate or change to MiC without proper incentives [22].

One of the incentives that can be done is to provide some tax relief measures to promote for the adoption of MiC, this can lessen the initial costs of the projects and encourage companies to adopt MiC, and this can help in overcoming the challenges facing MiC. Furthermore, many countries lack special legalization and international standard specifically made for MiC, the pioneer in this action is the Danish government who made the world's first modulus system legalization and standards [20, 24]. In this section, we tried to cover the important and common challenges that are hindering the growth of MiC, but this doesn't mean that these are the only challenges existing. The literature mentioned more challenges like lack of experience in module installation, lack of design experience, decreased flexibility for late design changes, requirement of early commitment [19], lack of large capacity hoisting equipment, product quality problems [20] and lack manufacturing capability [9, 20].

In addition, it is worth mentioning that we have discussed the details of challenges that were present in multiple literature not a specific one. Some advanced studies identified the challenges in certain markets and ranked those challenges then discussed possible solutions. Table 2, provides the ranking of different challenges to adopt MiC in two studies in two different countries; one was carried on prefabrication in general for the Chinese market [20] while the other studied MiC challenges in Singapore [19].

Table 2. Ranking of Challenges based on specific studies in different construction markets

Market Location	China	Singapore
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Challenges	Zhang, et al. [20]	Hwang, et al. [19]
Initial Cost	1st	5th
Logistics & Transportation	N/A	3rd & 8th
Coordination, Communication & Planning	N/A	1st & 10th
Lack of Knowledge	N/A	13th
Site Processes	N/R	9th
Lack of Standards & Supply chain	4th & 5th	N/A
Lack of Government support	6th	N/A

Notes: N/A: Not Applicable N/R: Not ranked/Out of ranking

5. MiC in Hong Kong

In April 2018, an International Conference on Modular Integrated Construction was organized by the Construction Industry Council (CIC) and the Development Bureau (DEVB) in Hong Kong, many experts from all over the world were invited. The aim of the conference was to build an understanding of this new method trends worldwide along with the development opportunities and challenges facing it [25]. In the fiscal year 2018-2019, the Hong Kong Special Administrative Region (HKSAR) represented by its financial secretary proposed USD one Billion as Construction Innovation and Technology Fund (CITF). MiC was one of the new technologies that the aforesaid fund supports. This aims to promote the usage of MiC because of how this method can offer in terms of productivity, quality and sustainability [25]. In January 2019, the CIC organized a “Client Contractor Supplier Forum on MiC”. Speakers were invited from the various Housing parties and academic experts as well. The aim of this forum is to draw a road map for the development of MiC and its challenges. The forum had a session for discussion between construction parties to help smoothening the project processes, such as; planning, design, procurement and government regulations [25].

MiC had a ground breaking in Hong Kong with its first pilot project starting in September 2018, this new project is a disciplined services quarter for the Fire Services Departmental at Pak Shing Kok, Tseng Kwan O. The project consists of 5 quarter blocks, each of height 16 to 17 stories, each floor shall contain around 8 modules and the total shall be 648 modules. Around 50 m² will be dedicated for three bedrooms, a living room, a dining room, a kitchen and a bathroom. Building facilities will include building management office, covered walkways and recreational spaces such as multi-function room, an outdoor playground for children, car park, etc. The project is expected to be finished in 2021 [25]. The second MiC project in the history of Hong Kong is the students’ residence at Wong Chuk Hang site owned by the University of Hong Kong. It is expected to be completed before the fourth quarter of 2023. The project consists of two 17-story residential towers on top of a three-story podium structure. It will contain single rooms of an area 6.5 m² utilized by students and staff, also the building includes recreational spaces, canteen, car park, etc [25].

6. CONCLUSION

From our review, we can conclude that MiC is the most modern technique available for the construction of buildings and it represents the future of construction, with its various benefits and what it can offer to the construction sector we can say that this method can be relied on in solving the problems of our industry, such as; sustainability, quality, time, etc. In addition, MiC can provide a universal solution for housing problems in some countries and cities like Hong Kong, its rapid execution feature increases its competitiveness against other methods. Nevertheless, the challenges facing MiC are crucial and can

prevent this technique from spreading, that's why providing solutions for these challenges is a must. We aim that this paper provides the Hong Kong construction sector insights on how to benefit from MiC and alerts regarding the possible challenges that they might face during the implementation.

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XII. BIM-ENABLED AEC APPLICATIONS IV (D3)

Determinants for Students Perceived Potential of BIM Use

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Abstract: Newly graduated students are shown to constitute an important source of innovation within the architectural, engineering and construction (AEC) industry. In relation to digital technologies like BIM (Building Information Modelling) that is claimed to have a potential to transform the industry, newly graduated students may play a vital role in innovating with BIM. The paper aims to explore determinants for students perceived potential of BIM use (PPBU) and the role of the educational background. The aim will be achieved by analysing the results from a survey conducted among third- and fourth-year students in construction and civil engineering in Hong Kong, Sweden, and Thailand (n = 194). When the different groups are compared Swedish and Thai students perceive a significant higher PPBU than Hong Kong students. In a step-wise multiple regression analysis five predictors for PPBU were identified for Thai respectively Swedish students, and one predictor was identified for Hong Kong students. It is concluded that in the contemporary BIM-discourse it is claimed that BIM can/should transform the industry, and BIM is even seen as a disruptive technology, and newly graduated students will contribute to (digitally driven) innovation. However, from the predictors of PPBU, the question can be raised if the awareness of the need for structural changes is lacking in the education, if students later in their working life should contribute to a BIM-induced transformation of the industry?

Key words: Building Information Modelling (BIM), Perceived potential of BIM use (PPBU), Surveys, Students, International comparison

1. INTRODUCTION

Newly graduated students are shown to constitute an important source of innovation within the architectural, engineering and construction (AEC) industry [1,2]. In relation to digital technologies like BIM (Building Information Modelling), which is claimed to have a potential to transform the industry, newly graduated students may play a vital role in innovating with BIM. For example, it has been shown that construction engineering students perceive a higher practical usefulness of BIM, compared to employees in the industry [3]. However, it is well known that perceptions of a technology vary among groups and over time [4]. As with other technologies, BIM has an interpretive flexibility (see also [5]). It can for example be perceived as a software application, a process for designing and documenting building information, or a whole new approach to develop the profession requiring new policies, relationships between stakeholders as well as new contracts [6]. In information systems research, it is well known that peoples' perceptions of a technology shape how information and communication technologies' (ICT) are used day by day, as well as their understandings of possible or actual pre-conditions and consequences connected with technology use [7, 3]. Consequences and pre-conditions can be connected to potential benefits of technology use and changes needed in order to realize the potential benefits, as well as influences of the organizational context.

Hence, if students entering the industry would contribute to BIM-induced changes, it can be claimed that they need to be aware of BIM's potential and preconditions for realizing the potential. Even if the "potential of BIM" or "full potential of BIM" is frequently mentioned in the scholarly literature (see e.g. [8, 9]), the potential is vaguely defined. In this paper, BIM's potential will be captured by the perceived potential of BIM use (PPBU), which is operationalized by measuring students perceptions of the usefulness of different BIM applications (see also [10, 3]).

Moreover, if students would become an important source of innovation by means of BIM, they not only need to perceive the potential benefits of BIM use. As important is that they have an understanding of the preconditions of realizing potential benefits, this is, being able of identifying variables, or factors shaping the realization of benefits. Accordingly can the question be raised if students merely perceive a direct correlation between BIM use and the realization of its potential? Or, do students perceive a more complex relation between the realization of BIM's potential benefits and the influence of the context in which BIM is used? And, how does the educational background influence students perceptions of BIM?

Given this background, this research paper aims to explore determinants for students PPBU and the role of the educational background. The aim will be achieved by analysing the results from a survey conducted among third- and fourth-years students in construction and civil engineering in Hong Kong, Sweden, and Thailand ($n = 194$).

The remainder of the paper is divided into five sections. In the following section, a conceptual framework for adoption and use of ICT (Information and Communication technologies) is presented, as well as how the perceived potential of BIM use (PPBU) is operationalized. In third section, approaches to data collection and analysis is described. In the fourth section, the empirical results of a multiple regression analysis is presented. Finally, a concluding discussion is presented in the last section.

2. REVIEW OF FACTORS INFLUENCING PERCEIVED POTENTIAL OF BIM USE

In research on adoption and use of information systems several factors have been identified as explanations for why and how a technology is used. Examples of these factors are: benefits of technology adoption; perceptions of the technology itself, need for change, collaboration, and external drivers and barriers. Benefits of technology adoption may be the first factor that comes into mind when it should be explained why and how a technology is used. The "benefit" is an important factor in the diffusion of innovation literature (see e.g. [11]). Especially the concept of relative advantage, this is, perceived benefits or expected advantages of using an innovation. Relative advantage refers to the expected advantages or perceived benefits that can be provided by an innovation to an organization [11, 12, 13]. The concept of relative advantage has also been one major influence on the technology acceptance model (TAM) where it is assumed that the perceived usefulness of a system predicts future user behaviour [14]. When perceived usefulness of an ICT application has been assed a construct with six items has traditionally been used ([14, 15]: 1) accomplishing tasks more quickly; 2) improving job performance; 3) increased job productivity; 4) enhancing job effectiveness; 5) making the job easier; 6) being useful on the job. The concept of perceived usefulness has been important to understand individual perceptions in pre- and post-adoption phases [16]. However, when studying benefits on the organizational level, Petter et al. [17] claim that there are insufficient data from the research to support any model that can be used to predict success on the organizational level. This observation is in line with the productivity paradox. This is, results from research focused on examining ICT's financial impact on productivity and firm performance and that has produced mixed results and invited researchers to consider mediating factors [18, 19]. Devaraj and Kohli [20] found that actual usage of technology is the missing link between ICT investment and its impact on organizational performance and showed that the driver of ICT impact is not the investment in the technology, but the actual usage of the technology.

If perceived benefits should be reached not only the consequences of technology adoption in terms of perceived usefulness, should be evaluated. Another important antecedent for the perceived benefits is the perceptions of the technology / system itself. In the literature on information system success ease of use and system quality has been factors these explains perceived benefits of a technology [17]. Important dimensions are for example; system reliability, ease of learning, system features of intuitiveness, as well as relevance-, understandability, accuracy of information [17].

The need for change if benefits from ICT would be achieved is well known in the research literature. A successful application of ICT is often supported by significant organizational changes, including workplace practice, organizational structure, rules and policies, and organizational culture [19, 21].

What is important to take into consideration is that technology can be seen as embedded in a complex and dynamic social context, where technology is neither an in-dependent, nor a dependent variable, but instead intertwined with the conditions of its use [22]. This is especially true for a technology like BIM, where an underlying assumption is that the technology would enable a seamless information flow, where value is co-created by the collaboration between stakeholders involved [23]. Finally there are external barriers for the adoption and use of an IS. These barrier are for example lack basic infrastructure, the educational level of potential employees, research and development investments [21], the role of institutional pressure [10], as well as incentives for external partners to cooperate [23].

To sum up. Based on the above literature, it could be pointed that PPBU could be influenced by technology characteristics, change management, and external influences.

2.1 Approaching of Perceived Potential of BIM Use

When BIM's potential, or the perceived potential is mentioned, the first issue to inquire is how the perceived potential of BIM use can be captured. In information systems research, different variants of the technology acceptance model (TAM) [14], have commonly been used to measure perceived usefulness of a technology. Thus, at the first glance it can be claimed that TAM could be used to measure the perceived potential of BIM use. TAM originates from the theory of reasoned action [25] and later by the theory of planned behaviour [26]. TRA/TPB state that 'behavioural intention' and subsequent behaviour is a function of an individual's attitude towards the behaviour - in this case, technology use-and his/her perception of the subjective norms promoting the behaviour. A subjective norm is 'a person's perception that most people who are important to her/him think s/he should or should not perform the behaviour in question' [27]. When TAM inspired frameworks are used for studying perceived usefulness of BIM, the usefulness is measured by perceived impacts of BIM, for example reduction of decision-making time, work task handling time, etc.[8]. Thus, TAM inspired frameworks can be appropriate for measuring perceived impacts of BIM use.

However, because BIM can be seen as an open multipurpose technology, there is a wide array of BIM-applications [10], these can be suggested to form the PPBU. DeSanctis and Poole [28] have a similar line of reasoning in their study on group decision systems. They found that studying a technology on the application, or feature level, instead of the artefact level, revealed that people used different applications, or features, in different ways that lead to insights how technology actually was used. Accordingly, using traditional TAM measures would imply statements like "Using BIM would enable me to accomplish tasks more quickly", or, "Using BIM will improve the quality of the work I do". These statements can have completely different meanings for the architect, structural engineer, contract manager, site manager, facility manager, as well as it is hard to know which BIM applications the questions are aimed at. For example, using BIM for clash detections is a very useful application for a structural engineer and a site manager, whereas the application is less useful for a facility manager. Accordingly, in this paper the PPBU will be measured on the application level and where the perceived usefulness of different BIM-applications will form the PPBU (see table 2).

3. METHOD

To explore determinants for students PPBU and the role of the educational background, a survey questionnaire was further developed from a study of BIM use among medium sized contractors. The suvery questionnaire contained four main sections of question, which were: 1) respondents background; 2) attitudes towards using IT; 3) BIM implementation practices; 4) Impact of BIM implementation. Sampling of data were gather from 3rd and 4th years bachelour students from Universities in Hong Kong, Sweden and Thailand. In this research, a multiple regression analysis (MRA) was adopted to analyse the data from questionnaire. MRA is used when predict the value a dependent variable based on the values of two or more independent variables [24].

3.1. Questionnaire Design and Data Collection

The questionnaire was earlier used in a study aiming at investigating attitudes to BIM among employees in medium sized contractor firms. In the survey to the students some statements had to be modified to fit the student context. For example, the statement "BIM can improve the quality of my work" was modified to: "BIM can improve the quality of work". In order to use the survey in Hong Kong and Thailand, the survey was first translated into English. This work was jointly done by the

researchers from Hong Kong and Sweden in order to validate that the meaning of the questions remained the same after the translation. Thereafter the questionnaire was reviewed by the Thai and Swedish researcher with the purpose of establish a joint understanding of the questions. Thereafter the questionnaire was translated into Thai, but the questions were written in both Thai and English.

In Sweden a web-link to the questionnaire was sent to the students via an e-mail. There after another two reminders were sent out to the students after one, respectively two weeks. In Hong Kong, the hardcopy survey was distributed to the students at the end of the class, and the electronic version of the survey was also distributed through e-mail to all students in building construction programme. In Thailand, the web-based survey was used as a tool to collect the student's perception. Researcher translated questions to local language and put into the web-based survey. The survey link was distributed to the students via direct email, social network, and colleague from other universities who teach BIM in Thai university.

In total 194 responses were received. The distribution of responses is showed in table 1.

Table: 1. Distribution of responses.

Country	Year 3	Year 4	Total
Sweden	70	0	70
Hong Kong	65	9	74
Thailand	15	35	50
Total	150	44	194

In Sweden the questionnaire was distributed to students in the end of their sixth and last semester. The Swedish student sample represents two different three years study programs: construction- and architectural engineering. Both programs encompass three BIM related courses corresponding to one semester full time studies (30 ECTS). The first course focus on providing basic skills in drawing standards and digital building information modelling as well as an insight into the use of collision control programs. The second course focus on the creation and use of information in a model, for example quantity take off, energy simulations and the creation of design specifications. The third course is project based and focus on the use of BIM for creating production specifications, as well as planning and control of projects for coordination and quality assurance.

In Hong Kong, the survey was distributed to all of the third and the forth (final) year students in two bachelor courses, including the BSc (Hons) in Surveying, and the BSc (Hons) in Building Engineering and Management. There is no standalone subject about BIM in both courses, but BIM-related knowledge and skills are integrated into various subjects, including information and data analysis subject, measurement and estimating subject etc., in both study programs.

In Thailand, there are two degrees that though BIM at Bachelor degree in Civil Engineering and Bachelor degree in Architecture. At the time of data collection, each university provided the specific subject for students to learn about BIM. The course provided the basic understanding of building information modeling, BIM process, BIM tools. The term project was established as one of the outcomes that students needed to be completed. It used as the learning activities to understand building information modelling. In addition, students also learn about BIM topics that are related to each subject.

3.2 Measuring Perceived Potential of BIM use

When developing the measure of PPBU, the point of departure is taken from Cao et al. [10] and Linderoth et al. [3]. Cao et al. [10] identified in a literature review 13 application areas for BIM in the design- and production stage when measuring the extent of BIM adoption. Building on Cao et al. [10] and Linderoth et al. [3], an instrument containing 14 items (application areas) for measuring the PPBU was developed. However, in this study, another two applications were added; documenting and transfer information, and simulation of the production process. In the survey the students got the question: "Based on your knowledge about BIM: How useful do you think BIM is for the following activities. 1= not useful at all, 2= not so useful, 3=neither nor, 4=rather useful, 5= very useful". The students' judgements of the activities are shown in table 2.

Table 2. Items for measuring perceived potential of BIM use

Items	Mean	Std. Deviation
1. Visualization in detailed design	4.40	.812
2. Clash controls	4.33	.879
3. Visualization for user	4.29	.822
4. Quantity take off	4.24	.801
5. Visualization production planning	4.22	.810
6. Documenting and transferring information	4.11	.812
7. Simulating the production process	4.07	.773
8. Cost estimation	4.05	.801
9. Site lay out	3.99	.887
10. Time planning	3.99	.874
11. Preparation for facility management	3.93	.845
12. Simulation of energy consumption	3.90	.899
13. Generate purchase plans	3.87	.828
14. Site logistics	3.86	.893
15. Staffing	3.74	.927
16. Environmental certification of buildings	3.69	.965

All applications were highly correlated with each other. From a principal component analysis (PCA with varimax rotation), we could see that all variables could be attributed to one single component (explaining 57.6 of total variance). Furthermore, an analysis of measure of internal consistency reviled a Cronbach's Alpha of .950 indicating a very high internal consistency [29]. Hence, we could create an additive index describing the perceived potential of BIM useBIM (PPBU), ranging from a theoretical minimum of 16 to a theoretical maximum of 80.

4. RESULTS

In this section, the results from the survey will be presented. First the results from the PPBU analysis and eventual differences between the different students groups will be presented and analyzed. There after the predictors for PPBU among the different student groups will be presented.

4.1. Perceived potential of BIM use (PPBU) and predictors

The first step in the analysis was to inquire the PPBU and if there were any differences between the countries, and finally to identify predictors for PPBU. In table 3 the mean values for the PPBU of the three student groups is presented.

Table 3. Mean values for students PPBU

Country	N	Mean	Std. deviation
Sweden	69	66.9	8.85
Hong Kong	73	60.3	11.17
Thailand	50	67.7	8.78
Total	192	64.6	10,31

From table 3 it can be seen that the mean values for Thai and Swedish students were rather similar, whereas the mean value for Hong Kong students were lower. The next step in the analysis was accordingly to investigate if there were some significant differences between the mean values. This was done via a one-way ANOVA test (table 4).

Table 4. One-way ANOVA test

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2220.719	2	1110.360	11.604	0.000
Within Groups	18084.260	189	95.684		
Total	20304.979	191			

The results from the one-way ANOVA test showed that there exists a significant difference between the groups. Accordingly, a Post Hoc Tukey test was conducted (Table 5).

Table 5. Post Hoc Tukey test

(I) Q0COUNTRY	(J) Q0COUNTRY	Mean	Difference	Sig.	95% Confidence Interval	
		(I-J)	Std. Error		Lower Bound	Upper Bound
Sweden	Hong Kong	6.66647*	1.64240	0.000	2.7866	10.5463
	Thailand	-0.74696	1.81670	0.911	-5.0386	3.5447
Hong Kong	Sweden	-6.66647*	1.64240	0.000	-10.5463	-2.7866
	Thailand	-7.41342*	1.79567	0.000	-11.6554	-3.1715
Thailand	Sweden	0.74696	1.81670	0.911	-3.5447	5.0386
	Hong Kong	7.41342*	1.79567	0.000	3.1715	11.6554

*. The mean difference is significant at the 0.05 level.

From the Post Hoc Tukey test it is revealed that there is a significant difference in PPBU between Hong Kong students on one side, and Swedish and Thai students on the other side. Between Swedish and Thai students were no significant differences for the PPBU. Thus, these results indicate the influence of the educational background, but the similarities between the Thai and Swedish student groups indicate that we have to go into deeper details in the analysis.

4.2. Predictors for perceived potential of BIM use (PPBU)

The final step in the analysis was to identify predictors for the PPBU among the three student groups. This analysis was done separately for each group to identify eventual differences among the groups and that could be a further indicator for the role of the educational background.

When analysing predictors for the Swedish student group a significant model was obtained by using the stepwise method, ($F 5.47 = 19.400$, $p < 0.000$, adjusted R square = 0.639) (table 6).

Table 6. Predictors for Swedish students PPBU

Model	Unstandardized Coefficients			Standardized Coefficients
	B	Std. Error	Beta	Sig.
BIM facilitates decisions these increase the quality of products and processes	2,819	1,259	,250	,030
BIM gives the company competitive advantages	2,950	1,249	,226	,022
BIM leads less errors, omissions and conflicts	3,642	1,129	,308	,002
BIM is of strategic importance for a contractor company	2,317	1,097	,199	,040
BIM facilitates decisions these decrease the company's environmental impact	2,039	,974	,218	,042

For the Swedish student group five predictors were identified and these had a rather similar strength and similar significance levels, even if the predictor [the use of BIM can lead to] "less errors, omissions and conflicts" is slightly stronger. The predictors are very much aligned with what students are taught in the BIM courses. Even if contractors view on BIM as a means for creating competitive advantages are very mixed, the students view competitive advantages as factors that is significantly correlated with PPBU. An explanation for this could be students' exposure for guest lectures from different software vendors and consultants who emphasize the need of adopting BIM in order to stay competitive.

When analysing predictors for the Thai student group a significant model was obtained by using the stepwise method, ($F 5.44 = 20.868$, $p < 0.000$, adjusted R square = 0.670) (table 7).

Table 7. Predictors for Thai students PPBU

Model	Unstandardized Coefficients		Standardized Coefficients	Sig.
	B	Std. Error	Beta	
BIM facilitates decisions these increase the quality of products and processes	7,937	1,262	,651	,000
BIM is of strategic importance for a contractor company	5,473	1,213	,443	,000
The model is too complicated	-1,822	,628	-,244	,006
Small contractors lack enough internal competence	2,083	,718	,255	,006
BIM gives the company competitive advantages	-3,710	1,398	-,305	,011

For the Thai student group five predictors were identified, but a bit contrary to the Swedish student group predictors vary more in strength and have a stronger significance. This predictors can be obtained from the learning of BIM concept and process, and also case studies that lectures provide in class.

The strongest predictor was “BIM facilitates decisions these increase the quality of products and processes”. An example of this is that BIM use could help to improve the process of model modification that will be reflected to other drawings and plans, which in turn reduce reworks or mistakes. The second strongest predictors was “BIM is of strategic importance for a contractor company”, which can be seen as a bit conradictive because the predictor “BIM gives the company competitive advantages” had a negative value. However, from a long-term viewpoint, it could be seen that BIM use for contractor can create the business opportunity by making the differentiate strategy when compare with contractors who not adopt BIM in their organization. But from a short-term viewpoint, students do not see the clear benefit from industrial cases that BIM use would bring competitive advantages today. Thus, students perceived that Thai construction industry do not see the competitive advantage today as they are starting the use of BIM, but advantages may come in the long term. Moreover, the Thai students felt that the competence on BIM use is perceived as essential to start use of BIM. It has the positive relation of BIM use because they felt that industry have this problem during the implementation. Based on the class seminar, several experts from the industry explains the issues of user’s competence. Therefore, student felt that lack of internal competence influence on the BIM use. Finally do the Thai students not perceive that models are too complicated. With regard to the perception of small contractors lack of internal competence, this is most probably the students own perception.

When the first regression model for the Hong Kong students was obtained, two predictors were identified “The use of BIM can lead to less errors, omissions and conflicts” and “BIM can support in making decisions these decrease the company’s cost”. However, the tolerance, $< 0,5$, indicated problems with collinearity. The two variables were combined into one. Using the stepwise method, a significant model was obtained ($F 1.64 = 135.169$, $p < 0.000$, adjusted R square = 0.674) (table 8).

Clash detection has been considered one of the fundamental functions of BIM.

Table 8. Predictors for Hong Kong students PPBU

Model	Unstandardized Coefficients		Standardized Coefficients	Sig.
	B	Std. Error	Beta	
Less errors/reduced cost	11,235	,966	,824	,000

The clash detection simulations were shown to the Hong Kong students in the classes, and they might have developed an impression of design error detection of BIM. In the same vein, Hong Kong students perceived the potential benefits of BIM use such as making design and construction site management decision which is important to contractors.

Respondents from Hong Kong are consisted of students from both building engineering management (BEM) and surveying (SUR) courses. A possible reason for the significance difference in PPBU between students in Hong Kong and Sweden Thailand was the diversity of the construction and surveying professions, including quantity surveying, general practices and building surveying, covered in the both courses. Perhaps, students who chose their undergraduate majors in construction

management (including building engineering management and quantity surveying), have developed a realization of the potential of BIM application on their professions than other students in other surveying majors. Students in other surveying majors might be unable to see the potential benefits of BIM technology, and how it is linked directly to the building surveying/general practices professions.

5. CONCLUDING DISCUSSION

The aim of the paper has been to explore determinants for students PPBU and the role of the educational background. When the determinants for the perceived potential of BIM use are closer examined, almost all predictors were connected to benefits of BIM use. The only exception was the Thai student group, where it was a negative correlation between PPBU and the predictor “the model is too complicated”. The integration of negative correlation is that the higher perceived potential of BIM uses a student has, the less complicated does s/he think the model is. This may be an expression for an uncomplicated view on technology where the most optimistic respondents, do not perceive any problems with complicated models. Or, students may underestimate the level of complicated model as they may focus only on structural and architectural model rather than mechanical and electrical model. Alternatively, the more knowledge a respondent has about the potential of BIM use, the less complicated s/he finds the model. What is notable is that none of predictors are related to changes in the way of working and in the way of collaborating. This may either indicate that students do not perceive that the items used for measuring the PPBU requires any changes in the way work and relations among parties are organized and regulated. Or, students may not perceive the complexities in the process when benefits of BIM would be realized? For example, using BIM for clash controls and visualization in detailed design, which were the two highest ranked items (see table 2), do not require any larger changes of work practices, whereas lower ranked items as the generation of purchase plans and staffing requires a more information rich model, that in turn put demands on how work is organised, and changes in roles and responsibilities. Nevertheless, as the differences regarding BIM and competitive advantages, and the similarities in the judgement of strategic importance between Thai and Swedish students shows a sensitivity for the context in which BIM would be used. This may also originate from the fact that contract of government in Thailand do not provide the requirement of BIM use as prequalification or BIM process but rather focus on the final model product that contractor have to submit at the end of project. (design – bid –build). Thus, even if the perceptions originate from lectures, students see the importance of BIM in both a short- and long-term perspective.

The role of the educational background, or what is taught in BIM-related courses has been obvious from the results. But, the most surprising results was that Thai and Swedish students had rather similar opinions with regard to predictors for PPBU, but Thai students' perceptions were more distinct with regard to the B coefficients and the significance level. This may be explained by the fact that Thai students are brought a rather comprehensive perspective on BIM, but contrary to the Swedish students, they have less hands-on experience with different software's that might explain the differences. Thus, Swedish students' perceptions have been moderated through their hand-on experiences. For the Hong Kong students the ,in general, limited exposure of construction management and surveying students in Hong Kong to diverse applications of BIM technologies may restrict their understanding of the BIM applications and the existing challenges. Perhaps, increasing the BIM contents in existing subjects, or develop a new subject for the innovation and applications of digital technologies and BIM would provide students a better picture of the benefits of disruptive technology, and help equip students with the necessary concept knowledge, skill, and ability to effectively deal with the BIM applications.

To conclude. In the contemporary BIM-discourse it is claimed that BIM can/should transform the industry, and BIM is even seen as a disruptive technology [30], and newly graduated students will contribute to (digitally driven) innovation. However, from the predictors of PPBU, the question can be raised if the awareness of the need for structural changes is lacking in the education, if students later in their working life should contribute to a BIM-induced transformation of the industry?

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XIII. RISK AND SAFETY MANAGEMENT IN CONSTRUCTION IV (E1)

Reliability Evaluation of Resilient Safety Culture Using Fault Tree Analysis

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Abstract: Safety culture is a collection of the beliefs, perceptions and values that employees share in relation to risks within an organisation. On the other hand, a resilient safety culture (RSC) means a culture with readiness of the organisation to respond effectively under stress, bounce back from shocks and continuously learn from them. RSC helps organisations to protect their interest which can be attributed to behavioural, psychological and managerial capabilities of the organization. Quantification of the degree of resilience in an organisation's safety culture can provide insights about the strong and weak links of the organisation's overall health and safety situation by identifying potential causes of system or sub-system failure. One of the major challenges of quantification of RSC is that the attributes that determine RSC need to be measured through constructs and indicators which are complex and often interrelated. In this paper, we address this challenge by applying a fault tree analysis (FTA) technique which can help analyse complex and interrelated constructs and indicators. The fault tree model of RSC is used to evaluate resilience levels of two organisations with remote and urban locations in order to demonstrate the failure path of the weak links in the RSC model.

Keywords: fault tree analysis, resilient safety culture, safety, reliability, resilience

1. INTRODUCTION

Modelling and analysis of RSC provides opportunity for understanding the mechanism of building a strong safety focus within an organisation so that lessons can be learned, and weaknesses can be addressed to prevent any future health and safety hazard. In an earlier study, the authors developed a RSC model and used it for identifying how remoteness of job location can impact the RSC [10]. In that model, RSC is defined as a function of psychological, behavioural and managerial factors. In the context of RSC, the psychological/cognitive capabilities of an organisation enable it to notice shifts from standard safe operational procedures, interpret unfamiliar situations, analyse options and figure out how to respond. Similarly, behavioural capabilities comprise of established safety behaviours and routines that enable an organisation to learn more about the situation, implement new safety routines and fully use its resources [3]. Managerial/contextual capabilities are a combination of interpersonal connections, resource stocks and supply lines that provide a foundation of quick safety actions [4].

Contribution of these factors within an organisation has been measured separately through combination of qualitative and quantitative methods but have never been used for estimation of RSC as part of a combined model [1, 2]. These three factors, on the other hand, are dynamic and always evolve

with time because of updates in the operational procedures, adoption of new technologies, changes in organisational structure etc. This also makes RSC dynamic over time [5]. Thus, often it becomes difficult to capture RSC of an organisation using a deterministic model. To address this issue, this paper develops and applies a probabilistic RSC model using a system fault analysis concept. Fault analysis techniques are generally used in systems safety and reliability assessment in order to provide a probabilistic estimation of the reliability of the system. We adopted this concept for modelling RSC so that a probabilistic estimation of RSC can be made.

There are many methods for system fault analysis including inductive and deductive approaches. In an inductive approach, failure states are examined and analysed. Examples of inductive approaches are Preliminary Hazard Analysis (PHA), Failure Mode Effect and Criticality Analysis (FMECA), Fault Hazard Analysis (FHA), Failure Mode and Effect Analysis (FMEA), and Event Tree Analysis (ETA) [7]. Drawback with inductive approaches is that the number of partial failure states tends to be too large, which makes it hard to determine all the possible causes of failures [8]. By contrast, a deductive analysis shows which failure modes has caused a system to fail [8]. Therefore, this deductive analysis would be better suitable for estimation of RSC as it would allow identifying major factors that are contributing to RSC. Quantitative FTA is a deductive risk analysis technique that effectively detects failures and quantifies probabilities of failure in a complex system [9]. Other advantages of using FTA is that it shows logical relationships between event and causes that lead to failure. It visualizes and helps quickly understand the results and pinpoint weaknesses in design and identify the errors. The FTA priorities issues since the fault paths can be understood and thus the user can choose where the resources need to be allocated. It also can be used for quality tests and maintenance procedures easily.

In this approach, it links a systems failure to all its subsystems and basic events that contribute to failure. Using FTA for the RSC model enables quantifying the overall probability of failure or inversely resilience level in an organization's safety culture but also relative probabilities of individual indicators, sub constructs and constructs.

Further, we first briefly present the RSC model and the FTA method highlighting its key features relevant to our analysis. Second, we present our RSC as a form of FTA model. Third, we applied this model to estimate RSC of two companies. Finally, we discuss implication of this model in increasing safety culture within an organisation.

2. RESILIENT SAFETY CULTURE MODEL

As mentioned before, the RSC model is based on three constructs: 1) Psychological/cognitive capabilities 2) Behavioural capabilities and 3) Managerial/contextual capabilities to anticipate, monitor, respond and learn in order to manage risks in a resilient organization. These three constructs are then divided into various Sub-constructs and indicators. In total there are 42 indicators in the whole RSC model. Details of our RSC model including these indicators and sub-constructs can be found in an earlier paper [6]. Figure 1 is the RSC model proposed in earlier publications [6, 10]. Figure 1 shows the RSC model where the resilience helps the system deflect any uncertainty or hazards which effect the system and thus enhancing the system performance.

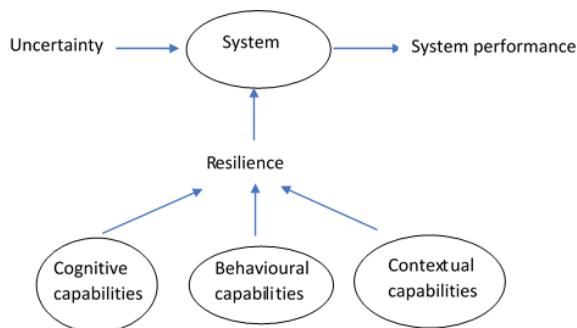


Figure 1: RSC model

Earlier studies proved that the psychological capability should be addressed then behavioural and then managerial for good functioning of the system [6]. In this paper, we use the FTA methodology to find the strengths and weaknesses of the linkages between indicators, sub-constructs and constructs and thus any weaknesses are addressed in the priority defined in earlier studies. Table 1 shows the relationships between constructs and sub-constructs. These sub-constructs further have indicators which shows the bottom most level in this pyramid model.

Table 1: RSC model with constructs and sub-constructs

Construct group#	Constructs	Sub-Construct Group #	Sub-Constructs
1	Psychological capability	1	Conceptual orientation
		2	Constructive sense making
2	Behavioural capability	3	Learned resourcefulness
		4	Counterintuitive agility
3	Managerial capability	5	Practical habits
		6	Behavioural preparedness
		7	Deep social capital
		8	Broad resource network
		9	Psychological safety
		10	Diffused power and accountability

3. FAULT TREE METHODOLOGY

A fault tree is a model that graphically and logically represents the various combinations of possible events, both at fault (i.e. when something goes wrong) and normal situation, occurring in a system that lead to the top event [11]. One distinguishing feature of the FTA is its visualised representation of logic sequences. Every logical operation is represented as a logic gate and connected to express the failure sequence of the system. Example of various gates is shown in figures 2 and 3. The event is denoted using a rectangle that results from the combination of events through the input of a logic gate. The circle denotes a basic fault event. The OR gate denotes that an output happens if one or more of the input event occurs. The OR gate provides a true (failure) output if one or more inputs are true (failures). On the other hand, the AND gate provides a true (failure) output if all the inputs are true (failures) [12].

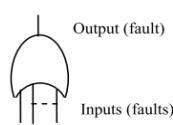


Figure 2: OR gate

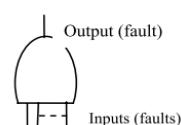


Figure 3: AND gate

The probabilities of occurrence of the OR gate are given by equation 1 and 2 [12], [13].

$$P(E_0) = 1 - \prod_{i=1}^n \{1 - P(E_i)\} \quad (1)$$

Where $P(E_0)$ is the probability of occurrence of the OR gate output event, E_0 , n is the number of independent input fault events, and $P(E_i)$ is the probability of occurrence of the input fault event E_i for $i=1, 2, 3\dots n$.

The OR gate corresponds to set union and probability of OR gate can also be written as follows:

$$P(A \text{ or } B) = P(A \cup B) = P(A) + P(B) - P(A \cap B) \quad (2)$$

The probabilities of occurrence of the AND gate are given by equation 3 and 4 [12],[13].

$$P(Y_0) = 1 - \prod_{i=1}^n P(Y_i) \quad (3)$$

Where $P(Y_0)$ is the probability of occurrence of the AND gate output event, Y_0 and $P(Y_i)$ is the probability of occurrence of the input fault event Y_i for $i=1, 2, 3\dots n$.

The AND gate represents a combination of independent events. This is equivalent to intersection of the input event set and probability of AND gate can also be written as follows:

$$P(A \text{ and } B) = P(A \cap B) = P(A)P(B) \quad (4)$$

4. FAULT TREE ANALYSIS OF RSC

As discussed in the previous section, FTA helps determining all possible situations that can result in the occurrence of undesirable event. We make analogy of this concept with RSC and in the case of RSC, the fault tree model can help to identify the probabilistic estimation of resilience (top event). The higher the probability of occurrence of individual construct and its sub constructs (downstream nodes of the fault free), the higher the probability of the safety culture to be more resilient. Probabilities of sub-constructs can be estimated by conducting a survey which is discussed in section 4.2. Figure 4 shows the proposed fault tree for RSC which includes 3 constructs and 10 sub constructs of our RSC model.

It is understood through literature that all the constructs of RSC follow an AND gate which is progressive relationship as defined by Cooper et al [2]. This is assumed that resilience level can only be achieved if employees can perceive about safety (psychological) and also have behavioural capability and have managerial system in place. In the absence of any of these three, there is no resilience in the culture. However, in the case of measuring sub-constructs and indicators, OR gates are used. This is mainly because OR gates are parallel relationship which allows achieving a construct (or sub-construct) partially even one sub-construct (or indicator) are absent. As an example, some degree of ‘Behavioural capability’ (which is a construct) within an organisation is possible to achieve even some of its measuring sub-constructs or indicators are absent.

It should be noted that the OR and AND gates are used in this study because it is assumed that the indicators, sub-constructs and constructs all follow the true relationships as defined. There is no cross relationship. This is the limitation and assumption of this study. Further work need to be done to understand these relationships more using structural equation modelling and other techniques and other gates can be used once this concept is validated.

Behavioural capability construct is used as an example to show the breakdown of FTA in more detail towards the events level. Figure 5 shows illustration of the construct “Behavioural capability” denoted by B_0 [15]. After OR gate, B_1, B_2, B_3, B_4 are its sub constructs namely “Learned resourcefulness”, “Counterintuitive agility”, “Practical habits”, Behavioural preparedness”. X_{10} to X_{24} are the basic events or indicators [6], [10]. There are 42 indicators in the whole RSC. Probabilities of achieving each constructs and sub-constructs can be estimated by conducting a survey among employees within the organisation.

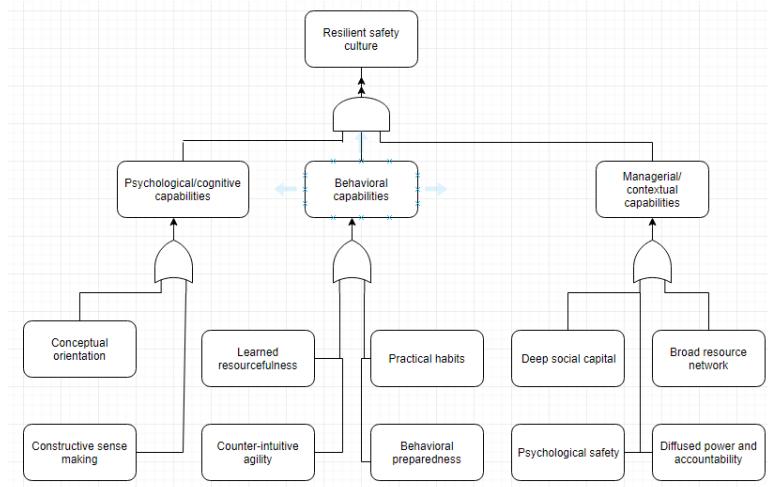


Figure 4: Proposed fault tree for resilient safety culture

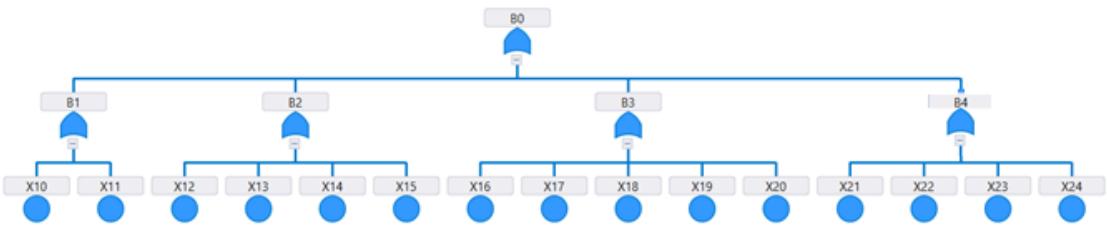


Figure 5: Proposed fault tree for “Behavioural capability” B₀.

Equation 5 shows the construct's probability which is calculated using summation of weighted sub constructs.

$$P = \sum_{i=1}^n a_i p_i \quad (5)$$

P is the relative probability of construct B₀, a is the factor weight and p is the probability of various sub constructs. The reliability probability of this sub-system is calculated using equation 4. P_{B₀} is the total probability of this sub-system where as p_1 is the probability of the node B₁ (sub construct) which is calculated using the equations 5 and 6 relationships using p_{10} and p_{11} likewise other probabilities like p_2 , p_3 , p_4 can be calculated. The weight of node B₁ is a_1 whereas a_{10} is the weight for node X₁₀ (indicator). Equation 6 calculates the probability for parallel relationships which means happening together since this system has OR gates.

It is assumed that the weightages are same for each indicator in same sub construct level and same weightage for each sub construct under similar construct level. The parallel relationships (OR gates) are independent of each other so they are assigned weights but progressive (AND gates) are not independent so no weights are assigned [14]. This is the construct level where no weights are assigned.

$$P_{B0} = a_1 p_1 + a_2 p_2 + a_3 p_3 + a_4 p_4 \quad (6)$$

$$p_1 = a_{10} p_{10} + a_{11} p_{11}$$

$$p_2 = a_{12} p_{12} + a_{13} p_{13} + a_{14} p_{14} + a_{15} p_{15}$$

$$p_3 = a_{16} p_{16} + a_{17} p_{17} + a_{18} p_{18} + a_{19} p_{19} + a_{20} p_{20}$$

$$p_4 = a_{21} p_{21} + a_{22} p_{22} + a_{23} p_{23} + a_{24} p_{24}$$

Finally, using equation 7, relative probability of the progression relationships (AND gate) is calculated which means factors happen in-sequence. Superior factor's (top event) probability is the product of inferior factors (all three constructs). In this case, equation 5 is used to calculate RSC.

$$P = \prod_{i=1}^3 p_i \quad (7)$$

4.1. Model application

In order to test the applicability of the FTA model of RSC, a survey was conducted using relevant items listed and discussed in the RSC model [6] and was given to employees working in two organizations X and Y. Both organizations have sites in rural and urban areas which show varying resilience levels in these organizations [10]. This variation thus gives a good case study to show how resilience level can be gauged and what probability of occurrences are for various constructs and sub constructs. This paper proposes a tool through which resilience levels of organizations can be gauged using the RSC survey and FTA methodology and thus help in comparison, resource allocation and weak paths. The importance of FTA is showing the weak paths and thus nodes which have low resilience levels from the indicator to the construct level. Unidirectional approach from indicators to subcontracts to RSC is taken while the resilience information is disseminated. It should be noted that once the weaknesses are visualized and calculated, the RSC model defined in earlier studies prioritizes the resource allocation. A flow chart in further sections will help understand the whole sequence in more detail.

4.2. Survey

. The location of surveyed sites thus helps in the variation in the resilience levels and helps in comparison and resource allocation studies. The surveys were completed by different employees including engineers, supervisors, managers. There was no limitation on who could fill the survey since the goal is to gauge the perception and other indicators of all employees working in these organizations about the safety culture. There were 42 items in the survey. Nine items were for “psychological capability”, fifteen items were for “behavioural capability” and eighteen items were for “managerial capability”. A total of forty two items were inferred using the various indicators of resilient safety culture model [6]. Likert scale from 1-5 was used to rate these items, where 1 on the low side or lower expectancy and 5 on the higher side or higher expectancy. An example of one of the questions asked in the survey was “Does your organization have a strong sense of purpose, core values and a genuine vision? The higher the Likert scale response better it is for the company since the resilience level is higher in that organization and so forth. For comparison to see the difference in resilience levels between remote and urban sites, data was first analysed using t-test.

4.3. Un-paired T test

Unpaired t test was performed for companies X and Y which provided comparable sample size data for urban and remote sites. The unpaired t test is used if the population means estimated by two independent samples differ significantly. For unpaired t test for company X, the two tailed P value is less than 0.0001 showing extremely statistically significant results. For the unpaired t test of company Y, the two tailed P value equals 0.0023. Similarly, showing this difference is considered to be highly statistically significant. Thus, the companies X and Y data can be used to decipher conclusions based on t test significance [10]. Hence, this data was further used as input for the FTA.

4.4. Analysis of results

The survey generated data which informed about each indicator or items present or absent in the various sites of both organizations. The higher the Likert scale probability the better the resilience level as previously explained in the earlier section 4.2. Tables 2, 3 show relative probability of occurrence for these sub constructs and constructs along with final organizational resilience levels. This resilience level (RL) can be seen by equation 8. It states that this data interprets probability of occurrence at indicators or event levels and this resonates to its resilience capability. So, if probability of failure is calculated for any event or any failure mode at any sub construct or construct level, it can be seen through equation 8.

$$\text{Failure probability (Top event)} = 1 - \text{resilience level (RL)} \quad (8)$$

Table 2 shows the company X and company Y resilience levels for urban and remote sites for all the sub constructs. These sub constructs fall under the three main constructs psychological, behavioural and managerial as shown in figure 4. For example, in table 2, probability of resilience for “Conceptual orientation” sub construct is 0.721 for remote sites which means the probability of failure is actually 0.279 for company X in remote site. This probability is purely based on the survey inputs. This can be a limitation for this type of study, the more the data better are the results and interpretation but since we are comparing two companies, it generally gives a good comparison trend.

Table2: Company X and Y remote and urban relative probability data for sub constructs

Sub-Construct Group #	RSC sub constructs	Remote	Urban	Remote	Urban
		Company X		Company Y	
1	Conceptual orientation	0.721	0.813	0.585	0.755
2	Constructive sense making	0.649	0.683	0.604	0.628
3	Learned resourcefulness	0.636	0.767	0.670	0.700
4	Counterintuitive agility	0.482	0.621	0.600	0.590
5	Practical habits	0.489	0.820	0.652	0.592
6	Behavioural preparedness	0.614	0.700	0.610	0.610
7	Deep social capital	0.649	0.804	0.611	0.714
8	Broad resource network	0.604	0.688	0.640	0.665
9	Psychological safety	0.621	0.663	0.595	0.625
10	Diffused power and accountability	0.614	0.742	0.625	0.745

Table 2 shows that “Conceptual orientation” has highest failure probability for remote sites for company Y whereas “Counterintuitive agility” for urban sites “Conceptual orientation” refers to company’s sense of purpose, direction, values and vision which motivates employees and helps allocate resources where needed [16].

Table 2 also shows “Counterintuitive agility” in both urban and remote sites as the failure mode for company X. This is because it is having the least resilience level (RL) of all the sub constructs listed and so Company X needs to enhance this sub construct and its corresponding indicators to increase its total resilience levels. “Counterintuitive agility” refers to the ability to follow dramatically different action from what is the norm in the organization. An organization which adopt unexpected and timely responses to environmental changes impacting the organization [2].

It is interesting to note that this study is about understanding the failure modes of safety culture or trying to quantify the reliability of safety culture in organizations even though there is no physical downtimes are in play. Table 3 shows the three constructs resilience levels (RL) compiled together using equation 6 and 7.

Table 3: Company X and Y remote and urban relative probability data for constructs

Construct Group #	RSC constructs	Remote	Urban	Remote	Urban
		Company X		Company Y	
1	Psychological capability	0.685	0.748	0.595	0.692

2	Behavioural capability	0.555	0.727	0.633	0.623
3	Managerial capability	0.622	0.724	0.618	0.687
	Total resilience probability (RL)	0.237	0.393	0.232	0.296
	Comparison percentage increase		65.8		27.5

It shows “Behavioural capability” having higher probability of failure at remote sites for company X. As seen earlier in table 2, “Counterintuitive agility” is a sub construct of “Behavioural capability” thus the failure mode for remote sites. Table 3 shows “Psychological capability” which has higher failure rate in remote sites as compared to “Behavioural capability” in urban sites in company Y.

Figure 6 illustrates the whole methodology giving an example the calculations carried out for the remote site for company X

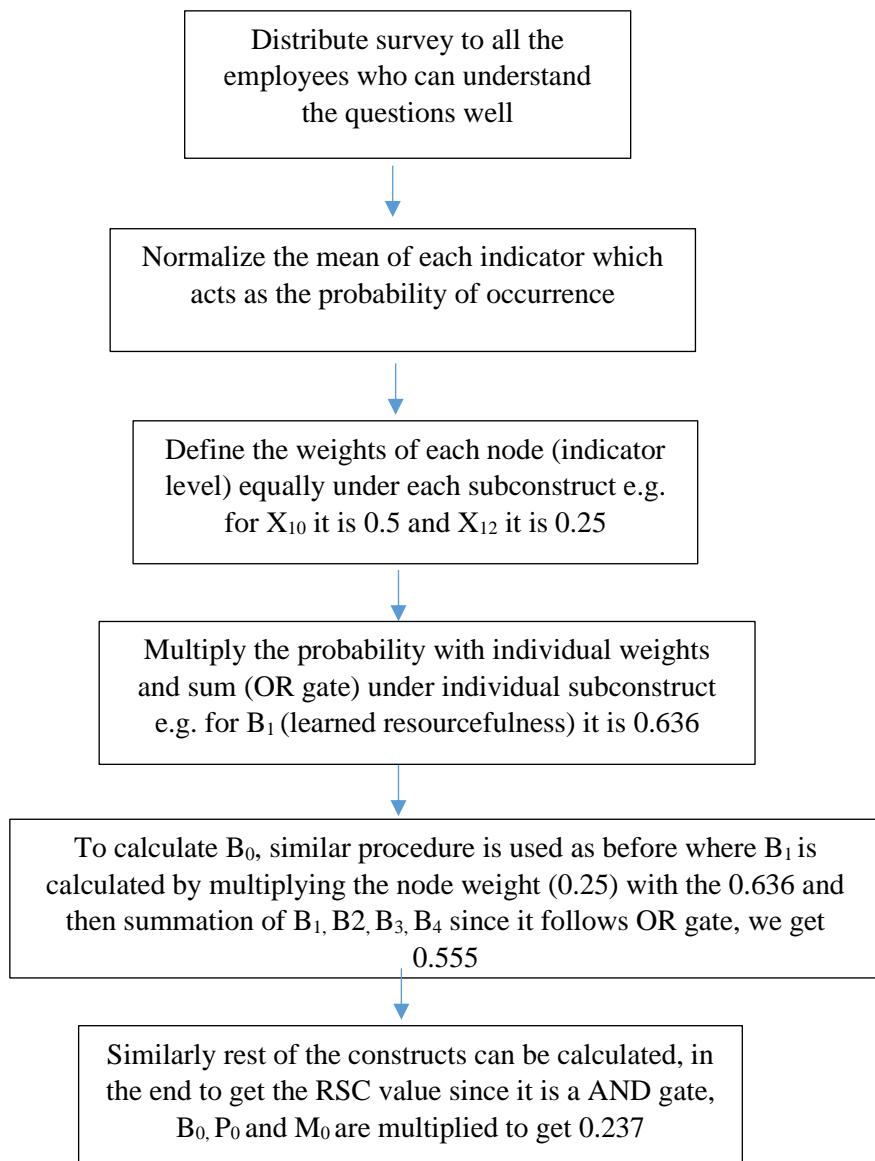


Figure 6: Flowchart showing steps to calculate the relative probability for RSC

5. DISCUSSION AND CONCLUSIONS

FTA detects weak points and unforeseen failure modes which is a strong feature of this methodology. This study thus finds resilience levels for remote sites less than urban sites. As seen in table 3, for company X, 65.8% resilience increase in urban sites as compared to remote sites. For company Y, 27.5% higher resilience levels in urban sites than remote sites.

Company X “Behavioural capability” shows the highest failure probability in remote sites and for company Y it was “Psychological capability” in remote sites. Comparing both companies, we find company Y was less resilient than company X both in remote and urban sites. Failure path for company X was through “Counterintuitive agility” and for the company Y was through “Conceptual orientation” in remote sites. If using this methodology, it is found that two indicators in two different subconstruct category and two different construct category needs resource allocation, the rule followed is first satiate the psychological capability, then behavioural capability and then managerial capability. If it is just under one construct but two different subconstruct, then priority is given to the lowest subconstruct.

The reliability of this RSC system is the probability that this system operates for a certain period of time without failing. This reliability is the resilience level of the RSC system. It will be of interest to the researchers to find out how much machine down time is responsible for each of the sub constructs of the RSC system. It is seen that the resilience levels are not very high in the remote and urban sites and this study shows which indicators or sub constructs create a failure mode which is responsible for this downtime. Further research need to quantify this downtime with respect to each of the sub constructs or failure modes. On positive note, it can also be concluded that even though the resilience levels were low in both remote and urban sites for both companies, the maximum RL was 0.393, there is lot of scope for improvement and this can impact greatly on the performance of the companies. Good resilient safety culture can enhance the output of the company greatly and thus companies should focus on not just physical machine downtimes but also resilience levels in their safety cultures.

In conclusion, this study shows how RSC can be captured quantitatively through this model and how this model can give pointers where the resources need to be added for enhancing resilience in an organization. It also shows the failure path in weak links of the RSC model. The limitation however is the information collected and used in the model is dependent on the amount of survey questions and number of surveyors.

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Joint Reasoning of Real-time Visual Risk Zone Identification and Numeric Checking for Construction Safety Management

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Abstract: The recognition of the risk hazards is a vital step to effectively prevent accidents on a construction site. The advanced development in computer vision systems and the availability of the large visual database related to construction site made it possible to take quick action in the event of human error and disaster situations that may occur during management supervision. Therefore, it is necessary to analyze the risk factors that need to be managed at the construction site and review appropriate and effective technical methods for each risk factor. This research focuses on analyzing Occupational Safety and Health Agency (OSHA) related to risk zone identification rules that can be adopted by the image recognition technology and classify their risk factors depending on the effective technical method. Therefore, this research developed a pattern-oriented classification of OSHA rules that can employ a large scale of safety hazard recognition. This research uses joint reasoning of risk zone Identification and numeric input by utilizing a stereo camera integrated with an image detection algorithm such as (YOLOv3) and Pyramid Stereo Matching Network (PSMNet). The research result identifies risk zones and raises alarm if a target object enters this zone. It also determines numerical information of a target, which recognizes the length, spacing, and angle of the target. Applying image detection joint logic algorithms might leverage the speed and accuracy of hazard detection due to merging more than one factor to prevent accidents in the job site.

Keywords: Risk Zone Identification, Numeric Checking, Image Recognition, Safety in Construction, Depth Estimation

1. INTRODUCTION

Despite various efforts to reduce the number of accidents and fatality in construction sites, construction Safety accidents are occurring continuously. safety in construction remains a critical issue. In the up to date records of the Occupational Safety and Health Administration (OSHA), 169 fatality cases of workers struck by vehicles where registered. The number of fatalities, wounds, and close misses is that they present liabilities that can be avoided. Safe development requires care and arranging all through the undertaking life-cycle, from the structure, through development arranging, through development execution, and reaching out into tasks and records [1]. The conventional safety management in the construction industry is time consuming, costly, inefficient, and hard to control in big size projects [2], [3]. Therefore, OSHA needs to be deeply analyzed and checked if the current state of the art advancement in automatic rule-checking technologies can adopt these rules to leverage a safe environment in the construction site.

Nowadays there has been advancement in construction monitoring and rule automatic checking such as drone monitoring and simulation, equipment/material connectivity and tracking, robotics and automated technology, sensors, and reporting platforms, building information modeling. However, most of these technologies include limitations by handling a specific task at a time. As a result, Image Recognition Technology (IRT) is the most economically efficient, complex pattern recognition, visual-based risk recognition which is similar to the safety manager visual judgment process [4]–[6].

Image recognition-related technologies have the advantage of being able to systematically identify destructive behavior and unsafe environments without affecting the productivity of workers in the field, with little additional cost to expand separate devices after system algorithms are deployed [7], [8]. Besides, the safety manager's discovery of risk factors is crucially dependent on visual judgment, and the application of the proposed technology to replace human eyes is very high [9]. Concurrently, this technology is considered effective in helping or replacing some of the observer's tasks, since the site usability can be ensured even in his absents [10]–[12]. Recent researches proposed an automated inspection system implementing rule-based algorithms and analyzed models automatically to detect danger and tolerate preventive actions. The prototype was developed to automatically reflect falls prevention measures such as covers, and temporary rails installed to prevent workers from falling in wholes [13], [14].

However, existing prior studies using visual recognition technology have been limited to studying the applicability of this technology and improving accuracy in several cases of the unsafe environment or risky behavior in the site, and for the proposed research system to be feasible in practical use, it is necessary to identify danger factors so that various hazards existing at the site can be detected simultaneously. Besides, this technology should be introduced in the optimal location at the Planning (PLAN) stage because it performs merely within the viewing line and generates vast amounts of data while transmitting and processing when used in the absolute space, depending on the location of the camera installation. Therefore, the state-of-the-art researches focusing on Rule checking safety detection and image detection technologies were reviewed and analyzed to determine risk zones around hazard objects and detect if any target (person) crossing it.

2. LITERATURE REVIEW

A thrust of scholars analyzed the risk factors that might occur during heavy equipment work and proposed a measure to recognize the danger by utilizing a stereo camera to non-electric-based technology. In the study, three major threat factors were identified: speed of equipment, access to perilous places, and proximity between two objects, and the study was conducted on loading, transporting, and unloading operations. This study developed an algorithm code based on C++ language and presented a way to judge threat factors on the visual base [15]. To attach Radio Frequency Identification (RFID) devices to heavy equipment to prevent workers and heavy equipment crashes such as excavators and cranes. By doing so, it was derived that it was sufficiently preventable in case of collision due to the failure of pre-inspection [16], [17]. Fang (2018) applied Faster-R-CNN to determine whether to wear a protective helmet for job site workers and randomly selected more than 100,000 construction worker image frames after filming at 25 job sites. The classification items were primarily divided into Weather, Illumination, Individual Posture, Visual range, and Occlusion, and 19 classifications were made according to the specific classification, which was applied to the Faster-R-CNN algorithm to effectively recognize workers who are not in the use of helmets [19]–[22].

To leverage the construction safety management tasks, various technologies such as automatic design, sensor, and location tracking are being developed. However, the sensor, location-based technology applied to prior studies must be equipped with relevant devices in the worker's body or helmet, thereby reducing the efficiency of the work [23], [24]. Besides, devices are installed on a per-target basis, additional work is done to manage various components, and overspending is inevitable as the scope of control increases.

The presented study aims to progressively expand the possible target of visual technology for automatic rule checking by exploring OSHA rules and construction job site accident history and then applying image detection algorithm measures for safety management in the planning and construction phase. The real-time object detection YOLOv3 with its accuracy and speed can be integrated with the stereo algorithms to detect and measure depth simultaneously [15], [25]. The state-of-the-art depth estimation using CNN lacks the means to exploit feature information of the stereo pair of images. Therefore, this research reasonably used Pyramid Stereo Matching Network (PSMNet) to specialize in the pyramid pooling and typically utilize 3D CNN to regularize cost volume [26], [27]. The state of the art researches employing image recognition was properly classified under three groups: scene based risk identification, location-based risk identification, and action-based risk identification [28]. However, this classification didn't cover the variety of safety control on the job site. Therefore, this research developed a pattern-oriented classification of OSHA rules that can employ joint reasoning of zone identification

and numeric checking in the construction job site by integrating YOLOv3 and PSMNet inside stereo depth camera.

3. METHODOLOGY

Numerical determination (length, spacing, angle)

Determine numeric information of a target, which includes numerical information of the length, spacing, and angle of the target and raise alarm when measurements are outside the acceptable threshold by comparison with the design literature or related statutes, and includes the installation interval and installation angle of the protective materials installed primarily for work during construction phases.

Risk zone identification

This type of risk assessment recognizes sets of the danger zone and checks whether workers enter or evacuate the determined zone. Examples include lifting work using cranes where the cargo traces path access zone should be controlled and prohibited to cross to prevent cargo passing over the workers' head as shown in Figure 1. Equally, it includes prohibiting the workers from entering the loading area to prevent struck or collision with the unloading machines such as forklifts.

The person-vehicle risk zone determination scenario was chosen (as highlighted in the yellow box) as a proof of concept to test whether it is possible to merge numeric determination and risk zone identification using one monitoring device. In this case, the numeric input will remain the minimum distance between the target which is the job site worker, and the hazardous object which represents the closest vehicle. The risk zone identification will be surrounding the vehicle boundaries to determine whether a target will enter or exit this zone. The numeric input and the risk zone diameter will depend on OSHA rules that are pre-defined and are used as input in the below algorithm as illustrated in Figure 2.

The methodological framework consists of five steps. The risk zone diameter and numeric input are referenced inside the kitti stereo data scene flow 2015 algorithms. In the second step, YOLOv3 algorithms run the stereo camera recording and detect the target (person) and hazard object (car). The third step runs the PSMNet algorithms to determine the distance between the camera-target (person) and camera- hazard object (car 1). In the fourth step, the research uses a mathematical triangulation equation to calculate the distance between the target (person) and the hazard object (car 1). In the final step, the algorithm determines the risk zone boundaries, distance to the target, and draw a red box if the target enters the risk zone as illustrated in Figure 2.

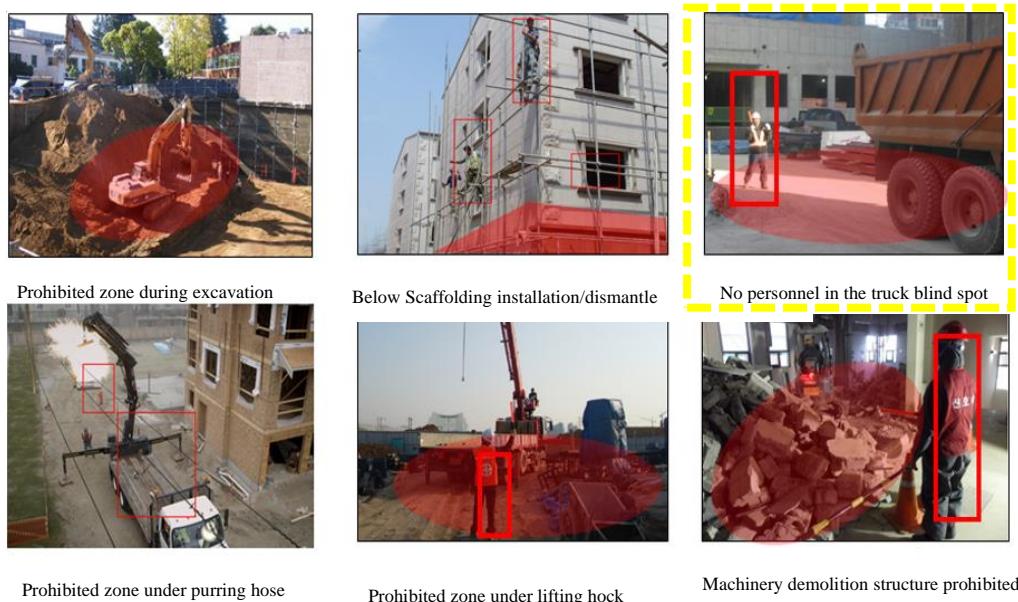


Figure 1. Different scenarios of determining prohibited zone during construction

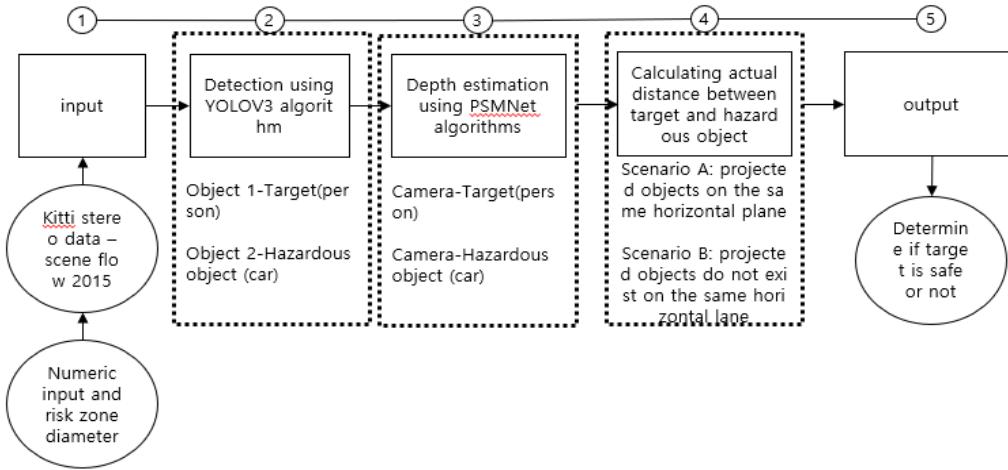


Figure 2. Research methodology framework

4. PROOF OF CONCEPT

4.1. Input

The numeric input and risk zone identification determined in the OSHA rules were pre-defined and adjusted to work for this specific example. The kitti stereo depth data – scene flow evaluation 2015 kit [29] was used as input data. This benchmark contains RGB, monochrome GPS, and laser scanner. The value of stereo confidence left-right consistency check of disparity of the pre-recorded data set was also used as input in the kitti flow evaluation. Its benchmark consists of 400 training and testing scenes. The pixel disparity is estimated to be less than 5% which is vital to determine an accurate distance calculation close to the actual measurements. The data were used to train PSM-Net and test its results shown in Figure 3.



Figure 3. RGB images from kitti depth data – scene flow evaluation 2015

4.2. Detection

There-recorded data from the kitti stereo– scene flow evaluation 2015 was then inputted into YOLO v3 to detect the visible objects in the scene as illustrated in the figure below. Yolo v3 is a detection algorithm suitable for use in construction sites where real-time detection is possible. The output of Yolo v3. Percentage means confidence in the model. The next line is the coordinate influenced by the model and it is represented in pixels. For example, car 1's bounding box corner coordinates are left top is (624,163), right top is (1056,163), left bottom is (624,330) and right bottom is (1056,330). The target (person) and the closest hazardous object (car 1) were detected and verified. Their bounding box corner x and y coordinate data were extracted from YOLOv3 and stored for the depth estimation using a different algorithm as illustrated in Figure 4.

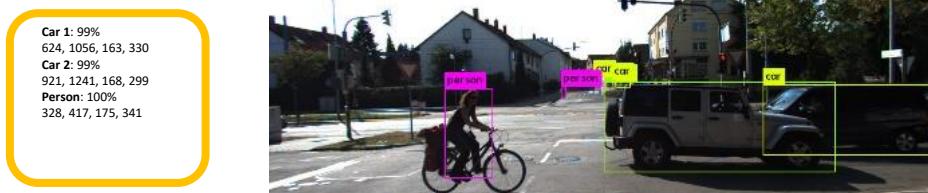


Figure 4. Image detection results in running YOLOv3 algorithms

4.3. Depth estimation

The same initial data are input into the deep learning network model (PSMNet). This algorithm extracted the feature values of the stereo/mono image and created a 2D feature map. Then it used 3D CNN to match cost computation. It finally predicted the disparity map. Each point in the disparity regression image represents the distance from the camera as shown in the below figure. The distance between camera-target (person) and camera-hazardous object (car) was extracted from the depth values. The final step is to Select the location-to-value of the detected Target and hazardous object in YOLOv3 to obtain the actual depth as illustrated in Figure 6. The center of the bounding box is considered the starting point to measure a straight line to the field of view center of the stereo camera when there is no overlap between objects Centers. However, Overlaid the center of the uncovered area will be the starting point to measure a start a linear measurement toward the field of view center of the stereo camera when the Object's Center Is Blocked.

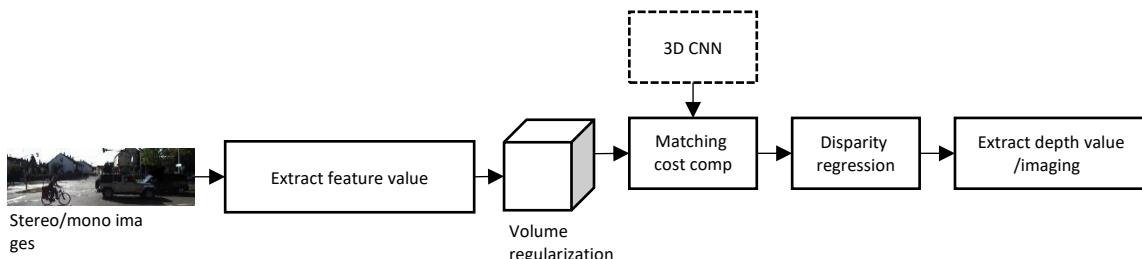


Figure 5. Deep learning model (PSMNet) working process



Figure 6. PSINet depth estimation regression map

4.4. Calculating the actual distance between the target object and the hazard object

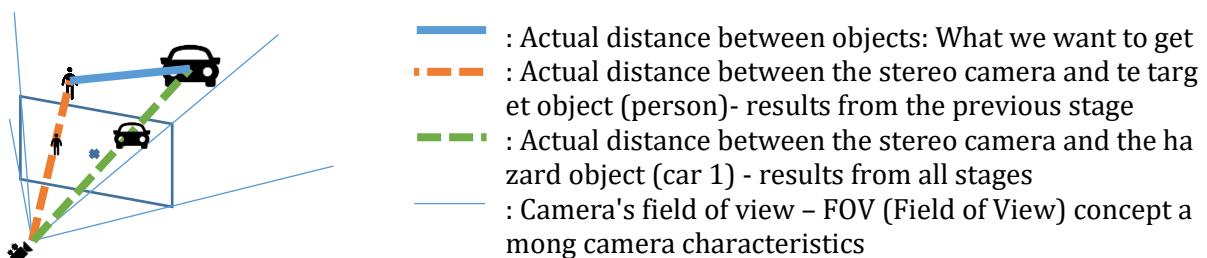


Figure 7. the relationship between the viewing angle of the stereo camera and the number of pixels

Scenario A: If the projected objects are on the same horizontal line (yellow line)

The green line in the middle of the below figure: Cross the center of the image in the direction in front of the stereo camera. As a result, the distance between the stereo camera and the target (person), the camera, and the hazardous object (car 1) can be calculated using the PSMNet output data. Then the actual distance between the target (person) and hazard object (car 1) can be found using the below formula as illustrated in Figure 8.

α : The angle between the camera's front vector and the camera to a person's vector

x: the number of pixels between a person and the center

width: number of lateral pixels in the image

$\tan(\text{visual}/2) = \text{width}/2/a$

$\tan(\alpha) = x/a$

$$\alpha = \arctan\left(\frac{2x\tan(\text{visual}/2)}{\text{width}}\right)$$

β can be obtained using the same formula

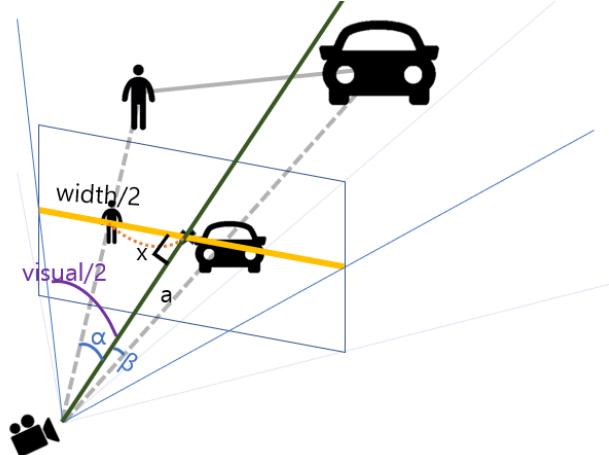


Figure 8. Step 4. Scenario A. projected objects on the same horizontal line

Scenario B. The projected objects do not exist on the same horizontal plane

If the target object (person) and the hazard object (car 1) do not exist on the same horizontal line, calculate the number of pixels between the original position and the moved position. In this case (a) can be generated by using the same value as the previous width FOV, where the dark green solid line is the distance * sin (α) from the stereo camera to the hazard object (car 1). The length of the yellow dotted line can be calculated by multiplying the length of the green dotted line by the cosine of (α) value. The length of the orange dotted line can be generated using the stereo camera depth calculation data. if the length of the yellow dotted line and the orange dotted line are known then draw a horizontal blue line between the target and the hazard object. As a result, the angle between the yellow dotted line and the orange dotted line can be calculated using the triangulation equation method shown in the previous example. Besides, the distance between the target (person) and the hazard object (car1) can also be generated using the previous triangulation equation as represented by the continuous blue line as shown in Figure 9.

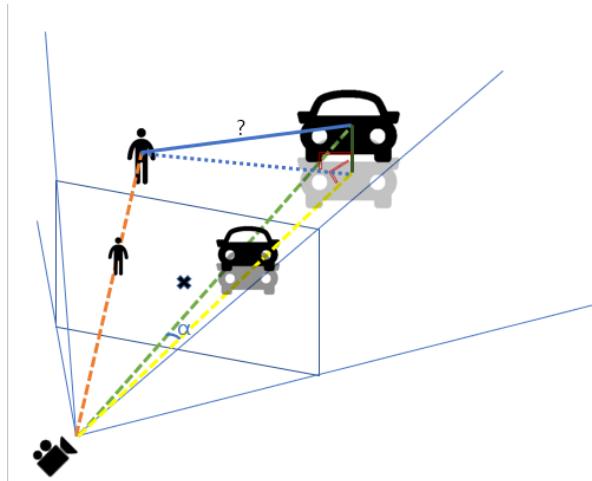


Figure 9. Step 4. Scenario B. projected objects, not on the same horizontal line

4.5. Output

In the illustrated scenario, If the distance between the target object and the hazardous object is closer than the specified distance determined in the OSHA rules or decided by the safety manager in the construction job site, the target object (person) is represented by a red box. Furthermore, an alarm should be sent to the target, hazardous object (car 1) operator and the Jobsite safety manager to eliminate the detected unsafe behavior as shown in the below figure.

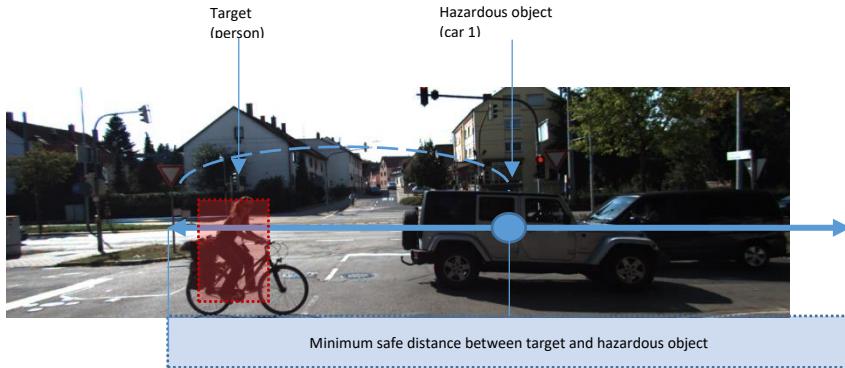


Figure 10. Illustration figure of the risk zone and target detecting red box

5. PROPOSED MONITORING ADVANCEMENT

The conventional numeric judgment is determined by using measurements after discovering facilities that are significantly in compliance with OSHA standards depending on the supervisor's experience and knowledge. If the allowable distance and allowable angle are exceeded, the nearby workers should seize work, reinstall the facility following the criteria then process work as illustrated in Figure 11.

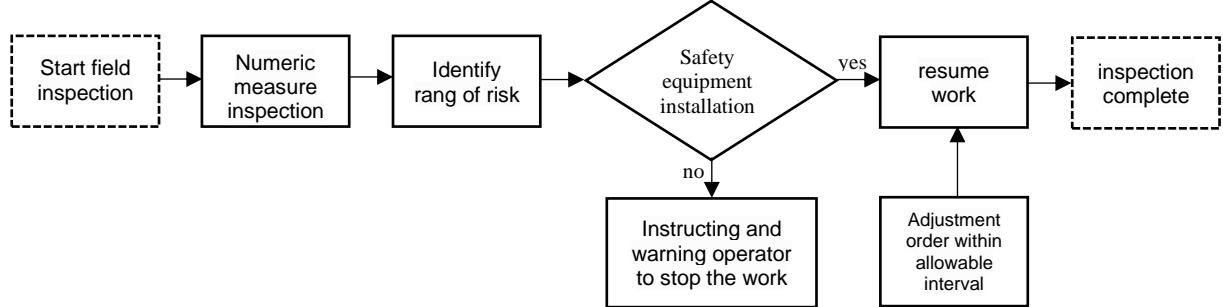


Figure 11. Conventional numeric inspection As-Is workflow

In contrast, when the proposed technology is applied on-site, it will be able to check and measure the protection, temporary kits installed and send warning automatically when they don't match the standards as presented in Figure 12.

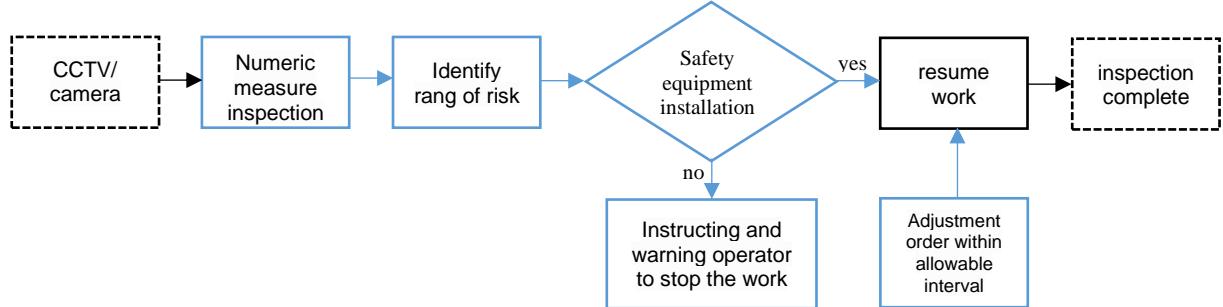


Figure 12. Numeric Determination to-be process

In the conventional risk zone identification workflow, the safety manager shall determine the place where access to the work should be prohibited and give direct instructions to the work team leader or guide/signal number, but it is not professional and often overlooked for the efficiency of the work as illustrated in Figure 13.

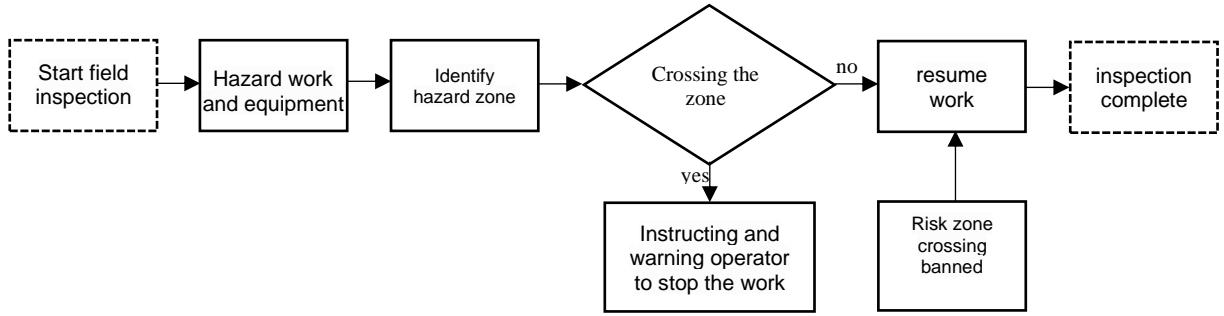


Figure 13. Risk zone As-Is workflow

The proposed methodology can reduce the workload by replacing some of the safety managers' tasks during the building process because of the constantly changing site conditions and the characteristics of the sites where various types of work occur simultaneously as illustrated in Figure 14.

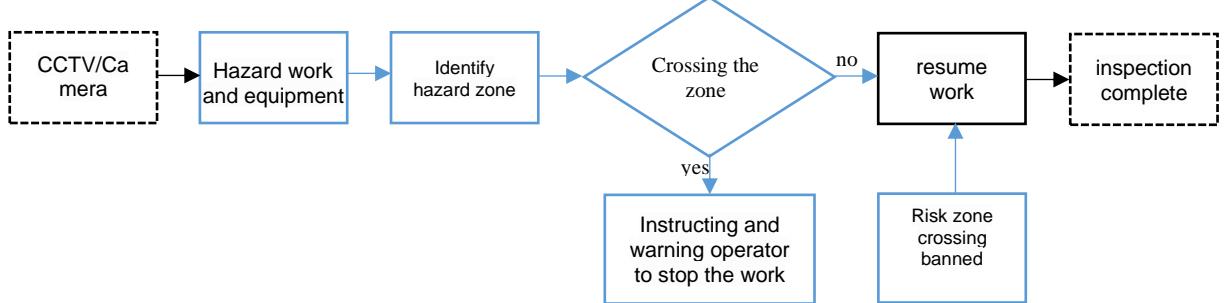


Figure 14. Risk zone identification To-Be workflow

5. DISCUSSION

The risk zone identification in the construction site in different scenarios shares similar characteristics such as occupying a circular space, preventing a target to enter or exit the zone, and having a fixed diameter. However, the numeric checking of this zone concerning a specific target (worker) might vary from one situation to another. For example, in the risk zone identification relationship between worker-vehicle is often horizontal. This research only covered one scenario which is worker-vehicle risk zone identification space and tested the algorithms for it. However, the relationship between worker-lifting hook is vertical which requires different numeric inputs. Therefore, the proposed algorithm should be modified for each activity independently. Also, for the risk zone identification and numeric checking to work, this research proposes integrating two different algorithms (YOLOv3 for image detection and PSMNet for depth calculation), which burden the monitoring and take a long time to process. It might be possible to merge both algorithms into one platform that detect objects and measure the distance between them simultaneously. This research only used the database prerecorded database of Kitti stereo depth– scene flow evaluation 2015 kit as a proof of concept. However, the construction Jobsite is a continuously changing environment with a variety of activities occurring at the same time, which makes the detection harder than the pre-recorded data that might add to the proposed methodology's challenges.

The process of recording the scene, importing it to the image detection algorithm, import the data of the detected object into PSMnet then finally calculate the distance and comparing it to OSHA rules is manual and consumes a lot of time. This research is pushing toward converting this process into a semi-automatic using only two platform one for detection and one for depth calculation. The rest steps are to be embedded within the two platform algorithms.

The proposed joint reasoning, risk detection, and numeric checking using image recognition technologies can replace or enhance the safety manager's performance in the construction job site. The conventional safety management takes a lot of time and lacks efficiency due to the requirement of physical existence at the Jobsite frequently. Therefore, the proposed method might be able to replace the safety manager's judgment of risk identification in the specific activities highlighted in the methodology section.

5. CONCLUSION AND FUTURE WORK

The integration between image detection YOLOv3 and PSMNet imbedded in the Stereo camera enabled the possibility to determine a risk zone identification around hazard object (e.g. Vehicle) and checks the numeric distance from the risk zone center of a target object (e.g. Worker) on the construction job site. Also, many researchers tried to reduce disasters in the construction site by applying image detection or depth estimation algorithms, but the limitation was fragmentary, and the focus of the research was on the applicability and accuracy of the technology. Recent scholars explored the possibility of reducing disasters in the construction job sites by applying image recognition technology, but the limitation was fragmentary, and the focus of the research was on the applicability and accuracy of the technology.

Therefore, to ensure the feasibility and applicability of the visual detection among the venture in the construction site, the risk factors are judged by the safety manager's visual and measurement tools. Furthermore, through the application of visual detection, the analysis process was automated to reduce the workload of safety managers who lacked manpower in sites. Due to the nature of the work of building, it is inevitable to rely on experience, along with visual judgment, and the inconvenience of the observer visiting the site exists.

In the future, test the same scenario using other available depth estimation algorithms such as the CSPN might give different valuable assets to risk zone identification in the construction job site. Also, the algorithm result can be tested using actual construction Jobsite PSMNnet physical data, photos instead of using prerecorded data available with the algorithm. Finally, PSMNet fine-tuning requires more learning data and ground truth to raise the accuracy of depth and distance prediction.

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Better Management (Risk and Change) through NEC Contracts in Hong Kong

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Abstract: Project delays, cost overruns, and disputes are becoming a norm for the construction industry in Hong Kong. Researchers argue that the inability of traditional contracts to manage risk and associated changes are perhaps the main points of contention. The Institution of Civil Engineers published a new engineering contract (NEC), NEC4 Suite of Contracts in this to facilitate better risk management through collaborative culture in construction projects. NEC aims to increase the chances of project success thought its flexible nature of contracts, 'simple' and 'clearly written' documents and provision for the incentive by adopting a better management approach. This paper focuses on traditional and NEC contracts to compare risk management and change management aspects. Through literature review and preliminary interviews with three industry professionals, the paper is exploring how a change in traditional contracts can recuperate from disaster. Our interviewees in this work have extensive experience in traditional as well as in NEC contracts. The results suggest a proactive risk management provisions in NEC contracts does make a difference to avoid later escalation of issues. Whereas, management of change helps streamline all identified issues through a structured process without going in mediation or litigation. NEC, with its new approach to collaborative working, allows partners to be vigilant, yet gratifying in the project process.

Key words: New engineering contracts, collaborative working, traditional contracts, project success.

1. INTRODUCTION

Delays, cost overruns, and disputes are perhaps the most common terms we hear about construction projects in Hong Kong and worldwide. The manifestation of this terminology is so common that even unskilled workers on site are well aware of them. One of the reasons pointed by the researchers is the adoption of traditional contracts in project procurement, which does not allow necessary flexibility.

Aim of traditional contracts is to allow different project partners, i.e., organizations to work together for constructing a facility within specific rules and obligations Walker and Rowlinson [1]. However, the blurred lines of risk allocation and change management in traditional contracts develop severe competition among project partners to safeguard their interest, leaving behind project objectives. Here we use a general term 'traditional contracts' to refer to most of the contracts that do not allow flexibility for the project partners to resolve issues amicably, e.g., general construction contract in Hong Kong. It is well understood that these type of contracts are designed to follow a structured approach that does not cater much of the needed flexibility to overcome the uncertainty project might face in the construction process. There are many examples of such contracts around the globe, which triggered a new research direction into collaborative contracting and later started a development into new engineering contract by Institution of Civil Engineers (ICE).

NEC with a family of flexible contracts enhances collaboration and success for all the project partners. Family of NEC4 contracts consists of fourteen individual contracts for managing the supply chain in the construction process Mitchell and Trebes [2]. In this, every single contract reflects the core philosophy of mutual trust and cooperation, together with specific project needs. It provides a customized solution for each project, yet maintaining a general principle of fairness. Two key aspects that differentiate NEC from most of the traditional contracts are risk management and change management procedures. Although risk and change management are connected through early warning system in NEC, it entails a powerful signal for project partners to feel secure in any of the unforeseen situations. This is where most of the traditional contracts are blank or blurred because most of the change events in the project execution stage involve substantial risk, which deviates attention from collaborative philosophy to self-centred one.

Thus, the paper focuses on the traditional and NEC contract to compare risk management and change management aspects. A comparison of both would help understand the essential characteristics, which facilitate NEC adoption decision for the clients. Traditional contracts rarely incorporate comprehensive pre-construction risk management measures (early warning system, etc.). Instead, deviate risk from one partner to another without considering appropriate management of those risks. It creates a fundamental issue with traditional contracts because delivery models are the one to provide a formal mechanism for risk allocation and management Osipova and Eriksson [3].

2. LITERATURE REVIEW

2.1. Traditional Forms of Contract

Traditional contracts usually follow strict guidelines for the project partners to fulfil their obligations. There is very little to no room for any change in the contractual responsibilities of the partners. Architects and other consultants are responsible for reflecting clients' ideas into workable drawings Ojo et al. [4]. The contractor then constructs the facility. The level of rigidity promoted by these contracts enables all the partners to focus on arm length relationship because all the partners are trying to achieve their separate objectives in the project. The linkage of traditional contracts with overall project success and the collaboration has been in research discussions, and there are two divergent views; the first view contends that the traditional contracts can ensure project success if the project partners focus on the social side of the projects Kadefors [5] and Pinto et al. [6]. The second view presents an opposing picture of the story to focus on enforceable measures to ensure project success. Both of the directions have contributed much in the general understanding of the construct of project success. However, it is evident now that traditional contracts are unable to meet the increasing demand of clients, adjust with more complex projects and collaboration among project partners. Thus, it is argued for the adoption of collaborative contracts in project delivery Memon et al. [7], Harper and Molenaar [8], and Ke et al. [9].

2.2. New Engineering Contract

New engineering contract (NEC) as a new family of contracts developed by the Institution of Civil Engineers United Kingdom (U.K.) to provide a contractual arrangement for engineering projects. NEC has been in practice from quite a while. However, it could not receive much attention from the industry. Until, Sir Michael Latham, who reviewed NEC as a part of his work for the U.K. construction industry. He termed it as the most modern contract to address issues in a project Latham [10]. Later, various projects in the U.K. and several other countries adopted one of NEC contracts in the delivery of projects. The Government of Hong Kong started using NEC in 2009 when the Drainage Services Department awarded the contract of "Improvement of Fuk Man Road Nullah in Sai Kung" project. It was a successful pilot project, completed six months ahead of time with a saving of 5% of the contract sum Drainage Services Department [11]. After completion of the project, various public and private sector clients in Hong Kong adopted NEC such as Development Bureau, Hong Kong Jockey Club. Since NEC is a new approach in Hong Kong. Development Bureau of the Hong Kong Government has developed practice notes in order to facilitate project partners for informed decision making in the project process Development Bureau [12].

Table 1: List of projects adopted NEC in Hong Kong adopted from the Construction Industry Council [13]

Contract Awarded in	Project Title
2009	Fuk Man Road Nullah Improvement Project in Sai Kung
2010	Retrofitting of Noise Barriers on Fanling Highway
2012	Happy Valley Underground Storm Water Storage Scheme
	Design and Construction of Tin Shui Wai Hospital
	Fresh Water Supply Improvement Project to Cheung Chau
	Management and Maintenance of High-Speed Roads in New Territories East and Hong Kong Island
2013	Improvement Works at Mui Wo, Phase 1
2014	Photovoltaic System at Siu Wo Wan Sewage Treatment Works
2015	Tseung Kwan O – Lam Tin Tunnel – Road P2 and Associated Works
2016	<ul style="list-style-type: none"> • Secondary School at Kai Tak Development • Central Kowloon Route • Cross Bay Link, Tseung Kwan O
2017	

This new form of contract focuses on three key elements to allow project partners to work effectively. These principles set guidelines for the partners to trust each other. Simplicity and clarity provide an essential guide for the client to write contract documents without any ambiguity. Whereas, later two principles focus on working with good intentions to protect self and partners' interest in a project.

Simplicity and Clarity

NEC contract provides clarity of the information to all project partners through clearly written all contract documents in simple language Mitchell and Trebes [2]. Therefore, NEC reduces chances of information asymmetry among project partners in comparison to traditional forms of contract Construction Industry Council [5]. 'Simplicity and clarity' are evident from clear roles & responsibilities, risk allocation, and procedures suggested adopting in any occurring situation Broome and Hayes [14]. Projects partners without any formal knowledge of NEC may be able to understand contract easily because of shorter clauses NEC [15].

Flexibility

The concept of flexibility in NEC is evident in its family of contracts. It is often confused that the NEC is a single contract providing solution for every problem in projects. NEC does provide a solution to most of the problems in projects but with its family of contracts. Thus, providing flexibility for the client to adopt any form of NEC contract based on a specific project. NEC offers a structured approach to adopt various kind of options together with core clauses; which are based on principles of mutual trust and cooperation. Project partners based on client requirement and agreement between partners adopt secondary options. This provides the most suitable combination of contract clauses for a project. The flexibility of NEC is also evident from the adoption in the Hong Kong construction industry, where NEC is adopted together with standard amendments in the contract (commonly known as Z clauses). These clauses used in addition to core clauses, main option, and secondary option. Dispute resolution approach in Hong Kong NEC is different from the standard approach in NEC. Standard amendments in NEC contract in Hong Kong contain dispute resolution methods to be followed in any Hong Kong NEC project Development Bureau [16].

Stimulus to Good Management

NEC characteristics involve the precise allocation of responsibility within a project setting. It provides structured procedures to adopt in managing change, notifying partner for any possible issue with good intentions. It improves partner's confidence to work collaboratively. In addition to this, NEC provides sanction for the partners to utilize in the time of need but are suggested to use as a last resort

3. RESEARCH DESIGN

Researchers adopted a two-step approach to address the aim of this study. In the first step, literature review on traditional and NEC contracts helped to formulate critical areas in this study. These aspects are risk management and change management. Later, these two aspects are substantiated by interviews with three industry professionals having experience in traditional as well as in NEC contracts in Hong Kong construction industry. All three participants were asked about the difference between risk management and change management in both contracts using open-ended questions.

Table 2: Interview Participants

Interview Participants	Type of Organization	Project
Project Engineer	Contractor	Sham Mong Road Footbridge Project
Engineer	Client	Happy Valley Underground Stormwater Storage Scheme
Engineer	Client	Sha-Tin Signature Project Scheme.

4. RESULTS

4.1. Risk Management

Risk management in traditional contracts

As mentioned in earlier sections, traditional contracts are designed to deviate risk from one or more partners to the contractor (in most cases). Thus, the issue of improper risk allocation is central in traditional contracts Walker and Rowlinson [1]. Poor risk allocation and management in traditional contracts is evident from the number of changes in the project program (variation orders). Because of unrealistic project program submitted at the bidding stage, the various issues may increase the risk of delays and cost overrun Mitchell and Trebes [2]. As the contracts would not incorporate any change at a later stage, all the anticipated risks and associated consideration are made while submitting bid documents. Any change in the state of the project during execution would call for a variation order from the contractor, thus start of a never-ending process of self-centred behaviours. In practice, the contractor at the bidding stage does not have adequate time to prepare a comprehensive program in traditional contracts together with risk considerations. They rely on post-contract contingency measures to mitigate risk in the construction phase Marco et al. [17]. However, these post-contract contingency measures may not help in changing some of the fundamental risk allocation issues agreed in the contract.

This is why traditional contracts are not suitable for developing, adopting a useful risk strategy in projects Robert [18]. These considerations made traditional contracts vulnerable to delays, cost overruns, and disputes in projects.

Risk management in NEC

NEC risk management approach allows project partners to manage risk efficiently and effectively. Risk management begins with early identification of possible risk areas in risk register by project partners in contract data one and two Mitchell & Trebes [2]. Thus allows identification, inclusion, and later discussion of any concerned area for project partners. This plays a foundation for building trust among project partners. Further, early warning meeting/risk reduction meeting discuss issues identified at length for a possible compensation event. According to the NEC clause 15.1, project partners are required to adopt early warning system so that they can notify each other on the risk related to time, cost and quality Mitchell and Trebes [2]. Early identification of possible risk is motivated by the substantial benefits/losses project partners can earn in the process Robert [18]. All three interview participants from three different NEC projects in Hong Kong mentioned the usefulness of early warning and risk reduction meetings (often known as early warning meetings in NEC contracts) to mitigate risk before they become points of contention for project partners and the project. In the first project, one interviewee pointed out

that concrete supply was one of the risks identified by the project partners — this initiated risk reduction meeting for consideration of the issue for possible actions. After a lengthy discussion during risk reduction meeting, project partners decided to extend the project completion date. The second issue arose in project two due to the difference in ground conditions (underground utilities such as water supply, draining, and cable wires) were different from the drawings provided to the contractor. By following the NEC early warning system, the contractor was able to draw attention from the project manager. The early response from the project manager and associated design team on the issue lead contractor work with enthusiasm because the contractor felt project partners cared about them. The last project involved a critical deadline in opening a thematic lighting system. Contractor feared a delay in meeting the project deadline because there was a delay in project initiation. Through an early warning notified by the contractor, project partners meet a crucial deadline by using a temporary cable system.

Summary – Risk management

Risk management in NEC encourages parties to think out of the box to solve problems before they become a point of dispute Patterson [19]. It allows them to limit the issue to a more controllable one in terms of time and cost to the project. A systematic approach in NEC for risk management ensures due diligence of all the risk through early warning and risk reduction meetings. In comparison to traditional contracts, repeated interaction for risk reduction meetings and a manifesto for achieving the best outcome of the project ensures early resolution for the risks Akintan and Morledge [20].

4.2. Management of Change

Management of change in traditional contracts

A change in the current state of the project or activity results in variation order, which would require additional costs and time for the project. Traditional contract manage change by notifying engineer to claim on additional cost and time Besaiso [21]. Since the change is linked to the final contract sum, it requires a structured procedure to manage. Unclear information in traditional contracts leads contractors to focus on claims to recover the additional cost in the project, thus focusing on the self-interest of partners Cunningham [22]. These increased costs are recoverable through claims usually with a higher rate in bills of quantity submitted to recover as much as the possible. This is why most of the claims end up in time-consuming disputes and legal cases among the contractual partners because there are no such formal sanctions to these 'action and response' periods for the claims in traditional contracts Garcha [23].

Apart from matters related to the cost of the project, time plays an essential role in the management of change in traditional contracts. Because the traditional approach in claim management involves lengthy discussions without assigning a particular timeline for the decisions, increases the likelihood of disputes, Tochaiwat, and Chovichien [24]. This is why construction claims in traditional contracts may increase project duration significantly.

Management of change in NEC

Management of change in NEC is carried with compensation events. It is a formal approach for dealing with any change that might result in an extension of time or cost in a project. NEC provides a clear procedure to adopt for managing any change through compensation event procedure. Based on the core philosophy of NEC contracts, any change in the project is informed to the concerned party, and it is discussed at length to decide if there will be any realistic claim/compensation event under NEC clause 62.1 Mitchell and Trebes [25]. The procedure involves a comprehensive review of the event proactively Construction Industry Council [13]. Therefore, all the issues related to change are managed amicably during discussions or through compensation event submission. Later, all the decisions are further reflected in the updated program to facilitate the construction works at the subsequent stage. NEC compensation event procedure allows partners to appropriately analyse and complete the procedure together with the risk provisions, thus enabling them to submit a realistic quotation for a compensation event. This is one of the essential features, which traditional contracts do not allow. The appropriate risk consideration at compensation event incentivizes the contractors to claim appropriate amount since they

are not required a higher compensation to offset with their risk. Interviewees pointed out that a transparent risk allocation in compensation event procedure increases chances of project completion on time. It prevents loss on both sides of the table and adopts a more realistic approach to the management of change in NEC projects. However, another interviewee highlighted the supervision of NEC compensation event procedure by the project manager to reduce chances for any other issue. A clear timeline for project partners in compensation event procedure motivates early resolution of the issues in NEC contracts. This facilitates the progress of works since the four steps in compensation events are governed by a definite time bar, pointed by another interviewee. If the contractors cannot handle the compensation events according to the time restriction, they will not be entitled to any compensation.

Summary – Management of Change

It is in the best interest of the project partners to ensure project success. The traditional approach to the management of change through claims have seen drastic results on the project and the relationship among project partners. Adoption of new ways of managing change could better establish the construct of project success and inter-organizational relationships. Because of the clear procedure, together with a strict timeline for managing change, would improve the interest of the partners to focus on mutual interest. This is further strengthened by early identification and submission for compensation event together with a proper risk assessment for each event Walker and Jonson [26]. These two improvements in NEC allows the parties to identify and resolve early to prevent larger compensation event that can cause the loss in the project Construction Industry Council [13]. In response to the overall benefits of compensation events for the project, interviewees pointed towards a healthy competition among the project partners.

5. CONCLUDING REMARKS

Comparison between the NEC and traditional forms of contract in terms of risk management and compensation event is discussed in the above sections. Evidence shows that NEC can bring benefits to the construction industry in Hong Kong in terms of better risk management and management of change. NEC provides a platform to develop and nurture collaboration among project partners with the best interest of the project in mind. Thereby reducing delays, cost overruns, and disputes among project partners. Earlier research has shown that improved collaboration among key stakeholders leads to collaborative behaviour [27] and improved performance.

This paper argues that the use of NEC in Hong Kong may improve collaboration among key stakeholders of the project. However, a small number of trained NEC professionals and dominant adversarial culture in the industry Jayantha et al. [28] are two main reasons behind the slow adoption of NEC. Both these issues are, however, manageable through extensive training of professionals on collaborative lines of thinking.

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XIV. SUSTAINABILITY CONSTRUCTION AND MANAGEMENT II (E2)

The Opportunities and Challenges of Implementing BEAM Plus in Hong Kong from the Perspectives of Government and Developers

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Abstract: Due to the enhancing environmental concerns worldwide with the need of increasing demand for sustainability of building design, maintenance and operation, key stakeholders including the government and developers in many countries strike for the benefits in implementing the green design and building concepts in constructing, infrastructure as well as the buildings. Different countries have their standards or certifications for green buildings while the adoption rate of BEAM-Plus in HK is relatively less compared with other developed countries such as Europe, USA and Japan. Therefore, in the present research, BEAM-Plus, the beginning assessment method of green standard implemented in HK, will be mainly discussed. Current situation of BEAM-Plus implementation in HK will be reviewed and then adopt a systematic approach via literature review and research paper, questionnaire with Analytic Hierarchy Process (AHP) method to depict the opportunities and challenges from the perspective of government and developers regarding implementing BEAM-Plus in HK and thus investigate the implementation gaps. It is found that for both the macro level of opportunity and challenge, the most important criterion is political, in which the weighting value are 0.3114 and 0.2321 respectively. It is obvious that government plays a critical and significant role in affecting the development of BEAM plus. Technological difficulty is also an important factor that challenging and hindering the implementation of BEAM plus, the weighting value is 0.2194 under challenge hierarchy. More experts and professionals should be imported to Hong Kong to enhance the technique is building green buildings. At the end of this paper, solutions and actions will also be suggested and concluded in alleviating the challenges. Finally, solutions and actions are suggested and concluded in alleviating the challenges. Findings from this research can guide developers to consider adopting green elements, government and Green Building Council in HK to review green buildings' policy.

Key words: BEAM Plus, opportunities, challenges, stakeholders, green

1. INTRODUCTION

There is an enhancing environmental concerns worldwide in construction and building together with the needs of keeping pace with the growing global demand for sustainable building design, construction, operations and maintenance and there are different countries have their standards or certifications for green buildings in different cities and countries. For example, Leadership in Energy and Environmental Design (LEED) in US, Green Mark Scheme (GMS) in Singapore, (Comprehensive Assessment System for Built Environment Efficiency (CASBEE) in Japan and BEAM Plus in Hong Kong. However, the proportion of green building and adoption rate of BEAM Plus in Hong Kong is relatively low compared to other developed countries such as Singapore. In this paper, BEAM Plus, which is the first building environmental assessment method implemented in Hong Kong for the promotion of green building practices, will be mainly discussed.

2. RESEARCH OBJECTIVES

- (1) To identify the key opportunities or motivations for the implementation of BEAM Plus from the perspectives of government and developers.
- (2) To identify the key challenges or barriers of the implementation of BEAM Plus from the perspectives of government and developers.
- (3) To investigate the gap between the perspectives of government and developers; and to make suggestions to facilitate the implementation of BEAM Plus.

3. LITERATURE REVIEW

3.1 Opportunities of implementing the Green Building Concept

There are empirical studies reporting various specific influences driving the current push towards Green Building development in different countries.

3.1.1 Opportunities in Hong Kong and Other Countries

Jayantha and Man (2013) [17] found that a sales price premium ranging from 3.4% to 6.4% is generated for housing units in building certified either for housing units in buildings certified with either HK-BEAM issued by the BEAM Society or the Green Building Award issued by the HKGBC. Qian (2016) [24] stated that Singapore not only promotes higher-tier green building rating which only projects certified with Green Mark Gold Plus or above can acquire the GFA concession, but also provides special financial incentives for professional such as engineers and architects to compensate for their extra time and effort that they have spent on Green Building. Fan, K., Chan, E. and Chau, C. (2018) [12] stated that Singapore government provides cash incentive to the developers and also project consultants for the new development which is at least 2 thousand sqm and achieves green mark gold rating or higher. The Singapore government has incorporated the green buildings into the city's master plan. According to the surveys conducted to CASBEE Professionals, Wong and Able (2014) [33] discovered that the top 3 incentives were priority reviews of green projects, following by the bank's preferential interest rates for a green development and building owners' financial incentives. Olubunmi, Xia and Skitmore, (2016) [23] stated a point that owners of the buildings applied green building concepts is due to the altruistic incentives which they believe the effects of climate change on human beings is real and they can put their effort to reduce the effect. The attracting financial and non-financial incentives motivate more and more developers to implement green building concepts in Hong Kong and other countries.

3. 2 Challenges of implementing the Green Building Concept

Zhang et al. (2012) [38] concluded there are 3 main challenges in applying green roof system for buildings in Hong Kong. They are "lacking of promotion to the public and private communities and promotion from the government", "lacking of the incentives from government on existing buildings" and "rise in maintenance cost". These challenges appear in the whole process of building cycle, from the very beginning to the completion of the construction. Townshend (2007) [31] also found lack of promotion from government is one of the hindering factors to the green roof building in Hong Kong. Other than that, Townshend (2007) [31] also outlined other barriers, which are the aging of existing building, poor utility arrangement, weak structural loading and lack of awareness in public and private sectors. Rather than the maintenance cost concluded by Zhang et al. (2012) [39], design, material, construction and transportation cost would be the critical cost-related factors. Besides, lack of completed integration among projects, experience, knowledge, standards, life cycle costing knowledge, time and funding are also the main barriers to the green buildings implementation.

3.3 Hong Kong and Overseas Practices in Green Building

3.3.1 Green Policies of Buildings in the World

Liu and Yu (2013) [21] reviewed that legal aspects from voluntary to mandatory tools were found as playing an essential role in promoting green building. Indeed, voluntary tools in regulations are found to be a great success in advancing the green building standard in developed countries in Europe, such

as UK and Netherlands. However, mandatory policies would be more effective on developing countries, such as Taiwan. They compared the policies between two Asian leaders on economic development.

3.3.2 Green Policy of Buildings in Hong Kong

In Hong Kong, there is no mandatory tool in green building requirement. According to Wong (2015) [36], Hong Kong Government adopts a target-based green performance framework. After reviewed the performance targets, new government buildings with a construction floor area for more than 5,000 sq. m. is targeted to attain “Gold” rating or above on BEAM Plus certification and a target on saving in total electricity consumption is set. It also proposed sustainable building design guidelines for the developers to follow. According to Wong (2015) [36], Building Energy Efficiency Ordinance was implemented in 2012. It requires the key building service installations of newly constructed buildings and existing buildings with major retrofitting works to comply. It also required the owners of commercial buildings to have energy audits once every 10 years to make sure energy efficiency. In 2009, the government launched the one off three-year Building Energy Efficiency Funding Schemes (BEEFS) to provide monetary allowance to building owners to conduct energy audits and implement energy efficiency improvement works.

4. RESEARCH METHODOLOGY

The research methodology of this paper consists of comprehensive literature review, existing research paper and report, questionnaires and survey and face-to-face structured interview.

4.1 Search Strategy

This research paper is following a systematic and structured processing method. Firstly, a deep search of publications about green building incentives or practise in HK and other countries are conducted from 28 Jan 2019 in large databases in Google and library of the Polyu. The study will be focused on keywords like “Green Building Incentives”, “BEAM Plus”, “Opportunities and Challenges of Green Building”, “Green Building Policies” resulted in more than 100 papers and publications. Secondly, titles and abstracts of those publications are addressed, which allows us to have an initial judgment of whether the publications are suitable and relevant or not. Thirdly, we have review the content of those publications.

4.2 Questionnaire – AHP Method

The structure and framework of the questionnaire survey mainly focus on how those respondents' thinking about the opportunities and challenges in the implementation of BEAM Plus in HK. At least 40 participants will be given the questionnaire. Target groups and participants consist of different stakeholder involving in property and construction related sectors such as designer, contractor, engineer and so on. A more comprehensive and precise result could be achieved by having a variety of opinions from different stakeholders. The questionnaire framework will be constructed based on the assessment model called “AHP” developed by Saaty (1980) [29]. Under AHP, the opportunities and challenges are classified into two separated hierarchies. Each hierarchy is divided into 3 levels. At the top level, it will be the optimal goal that we would like to find out through the questionnaire survey and quantitative calculation, that would be explained in details later. At level 2, it will be the macro- criteria and at level 3, it will be the micro- criteria.

1. Opportunity: In the Marco hierarchy, there are four areas including (1) political, (2) financial, (3) non-financial & altruistic and (4) internal. In the micro hierarchy, there are numbers of micro indicators under each marco-area. For example, under political criteria, there are the regulatory requirements; under financial criteria, there is price premium. All of the indicators have been concluded in the literature review of the opportunity part. The overall hierarchy has been shown in Figure 2 below.

2. Challenge: In the Marco hierarchy, there are five areas including political, financial, non-financial, internal and technological. In the micro hierarchy, there are numbers of micro criteria under each Marco-area. For example, under political criteria, there is the lack of government's promotion; under financial,

there are high maintenance costs. All of the indicators have been conclude in the literature review of the challenge part. The overall hierarchy has been shown in Figure 1 below. After constructing the hierarchy, pair-wise comparison matrix will be employed to give ranking and relative importance weight for the macro criteria and micro criteria. Respondents will be asked to assess the macro criteria and micro criteria between each other and they will appraise the relatively important weight for the criteria in macro level against the others in the same level. Same practice will be applied in the micro-level criteria. To make it easier, respondents will be asked to compare only the micro criteria against the other under each macro criteria, but not compare across the criteria under different macro criteria.

$$\text{Pair-wise comparison matrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix} \quad (1) \text{ Where } C_{ij} \text{ is the relatively importance score}$$

As well as we have numbers of respondents to the questionnaire; it is better to use geometric mean instead of arithmetic mean.

$$C = \sqrt[n]{C_1 \times C_2 \dots \times C_n} \quad (2)$$

Next, after collecting all the data, we will do the normalization for the matrix elements. The values in each column will be summed up and the values in the matrix will be divided by its column summed value to generate the normalized value X_{ij} .

$$X_{ij} = \frac{C_{ij}}{\sum_{i=1}^n C_{ij}} \quad (3) \quad \text{Normalized value} = \begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \end{bmatrix} \quad (4)$$

The values of normalized row will be summed up and divided by total number of criteria at the same column to find out the weighting value W_{ij} , or it can be said as eigen vector. It is a value that gives ranking to the criteria: the higher the value, the more important of the criteria. Normally, after calculating the eigen vector, eigenvalue model will be employed to find out the Consistency Index (CI). This is an issue happened frequently that the respondents do not give a consistent score to the pair-wise matrix. To avoid the consistency problem, only the first row will be shown in each of the pair-wise matrix table in the questionnaire. Respondents are not necessary to give score to the second row or below. Therefore, CI is not in the scope in this paper.

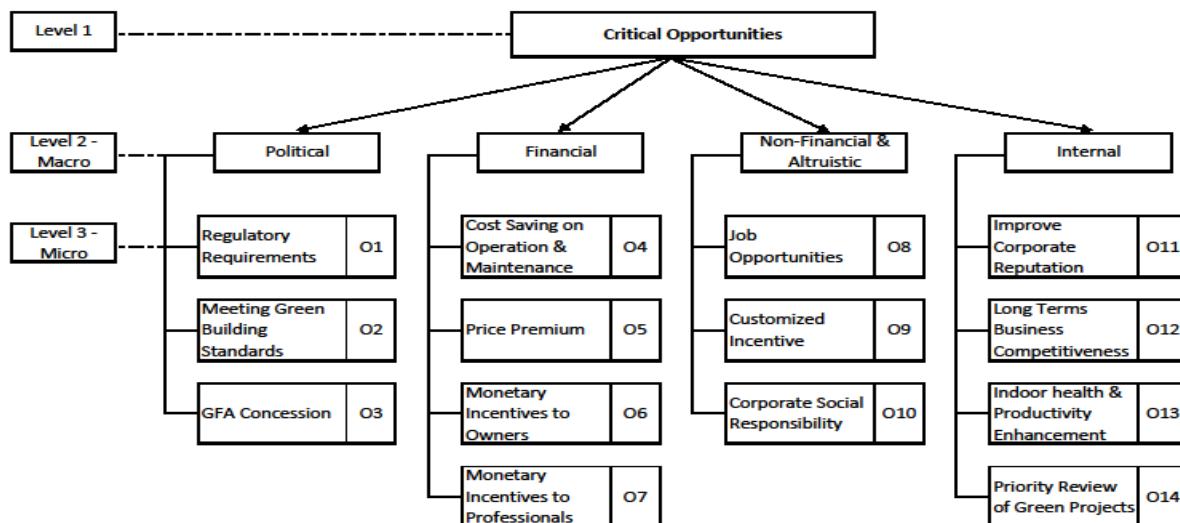


Fig. 1 – Hierarchy of Opportunity

5. Data Collection

Data were collected through the distribution of the questionnaire by different methods such as communication application tools (whatsapp and wechat), email or by hand. We have sent out 40 questionnaires to those who have involved and participated in green project and/or working in the property and construction related industries. Ultimately there are 31 questionnaires received, with a 77.5 percent reply rate. There are altogether 3 parts in each questionnaire. Part 1: the basic background of the

respondent. Part 2: Analytic Hierarchy Process (AHP): 11 comparison matrixes for potential opportunities and challenges in HK. Part 3: the comments or opinions on the existing BEAM Plus certificate and suggestion to advance the development.

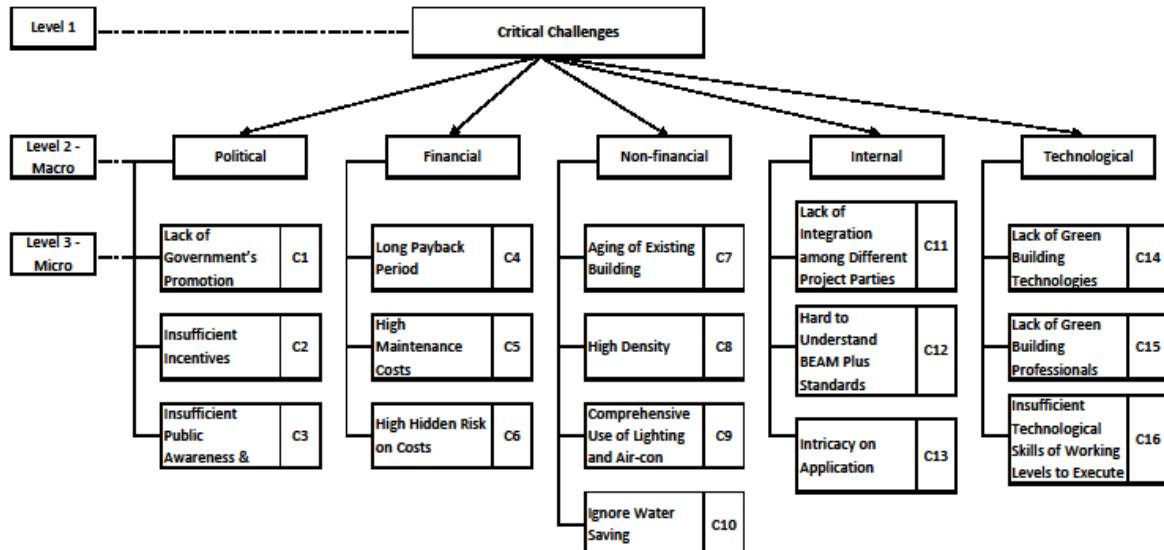


Fig. 2 – Hierarchy of Challenge

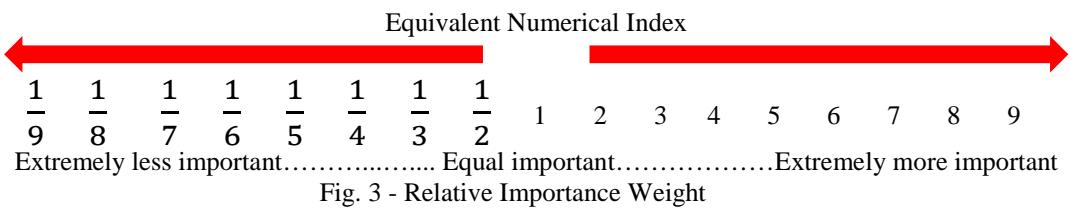


Fig. 3 - Relative Importance Weight

6. Research Findings

The following tables show the quantitative calculation result and the weighting value of every criterion, including both the macro and micro criteria, about the experienced respondents rating the importance of them.

6.1 Opportunity

Table 8 shows the weighting value of macro criteria under opportunity. Results show that Political factor has the highest average weighting value of 0.3114 and the second highest is Non-Financial & Altruistic factor, which has 0.2844. The lowest value is Financial criteria, which has only 0.1543. It implies political factor has the greatest impact on pushing the BEAM Plus implementation. Money and return is not an attractive motivation to the stakeholder. Table 9 shows the weighting value of Political criteria under opportunity. Results reflect “Meeting regulatory requirements” has the highest score of 0.4501, however, “GFA Concession” has the lowest value of 0.2624. The result shows one of the important successful factor is to meet the government regulation, instead of the green standard itself. Table 10 shows the weighting value of Financial criteria under opportunity. It can be seen that “Cost saving on operation and maintenance from efficient use of materials” has the highest value of 0.3567 and the second highest value is “Sales price or rent premium - Respond to customer demand on green building”, which has 0.2262. The third and lowest score is similar, and has 0.2088 and 0.2083. They are “Monetary incentives to owners e.g. Profit Tax reduction, subsidy and preferential interest rates offered by bank for green projects” and “Monetary incentives to professionals for inventing and implementing solutions and technologies on green building” respectively. The especially high score of “cost saving” show there would be a great opportunity and motivation in implementing BEAM Plus if cost can be saved from effective and efficient use of materials.

Table 11 shows the weighting value of Non-Financial & Altruistic criteria under opportunity. It is found that “Job opportunities created to the society” has the highest value of 0.3902. The lowest value

is “Corporate Social responsibility, reduction in construction pollution, energy and water saving and put effort to deal with global warming”, which has 0.2878. It seems the job created to the society would be the biggest diver in realizing the BEAM Plus under this criterion. Table 12 shows the weighting value of Internal criteria under opportunity. From the table, it shows the highest score belongs to “Improving corporate reputation and marketability”, which has 0.3806. “Enhancing indoor health and productivity” has the lowest score of 0.1927. It is surprised that respondents care less about the health bought from BEAM Plus. Instead, they think the reputation and marketability achieved by the company would be the largest opportunity in participating the BEAM Plus.

6.2 Challenge

Table 13 shows the weighting value of macro criteria under challenge. Results show that Political factor has the highest average weighting value of 0.2321 and the ranking is the same as in opportunity analysis. The second highest is Technological factor, which has 0.2194. Financial factor has the lowest value of only 0.1783. It shows government plays an important role in the BEAM Plus implementation. Without the help of government, it is difficult to gain success. Besides the issue of the government, insufficient technological skill is also an indispensable problem and challenges that hinders the BEAM Plus development. Again, money and cost is not a big obstacle. Table 14 shows the weighting value of Political criteria under challenge. It can be seen that “Lack of promotion from government” has the highest score of 0.4773. The lowest value belongs to “Insufficient incentives from government”, which has 0.2085. The promotion from government is a critical element to gain achievement. Lack of it will be a great barrier to the BEAM Plus implementation. Table 15 shows the weighting value of Financial criteria under challenge. Results show that “Incremental construction and investment costs with long payback period” has 0.4066, which is the largest value. The lowest value is “High maintenance cost”, which has 0.2284. It shows that the construction cost and long period of return on investment is the biggest concern among the investors. Once the green building is constructed, the maintenance cost is relatively less important.

Table 16 shows the weighting value of Non-Financial criteria under challenge. Results reflect that “Aging of existing building” has the highest score of 0.2687 and the second highest is “High density of HK”, which has 0.2479. “Comprehensive use of lighting and air conditioning” has the lowest score of 0.2385. The problem of aging buildings is a long issue in HK. Not surprisingly, it is the biggest barriers to the BEAM Plus implementation under this criterion as it is quite difficult to undertake a large renovation project on such old building. Table 17 shows the weighting value of Internal criteria under challenge. It is found that “Intricacy on applying BEAM Plus certificate” has the largest value of 0.3586. And “Lack of integration among different project parties” has the lowest value of 0.3146. It is clear that the complexity of applying the BEAM Plus is a crucial challenge and barrier. Before building a green building, it is necessary to submit dozens of documents and to fulfill a lot of standard requirement set up by government organization, such as Fire Safety Ordinance etc. Table 18 shows the weighting value of Technological criteria under challenge. Results indicate that “Lack of green building technologies” has the largest score of 0.4085. The lowest score belongs to “Lack of green building professionals”, which has 0.2826. HK is a place that is full of professionals in many fields. However, green practice is not really a mainstream in the construction industry HK. More skilled and experienced professionals are needed for the further BEAM Plus development.

All in all, under the opportunity hierarchy, Political factor is the most important among the macro level criteria. If the government could become the starter and driver in BEAM Plus, success will become easier. Under the challenge hierarchy, Political factor is also the most important criteria. In the growth and development of BEAM Plus, government could be the motivator and also be the obstacle. Without its help, implementing BEAM Plus would be a challenging task. The importance rating of the micro criteria of each macro criteria under opportunity and challenge hierarchy has also been discussed above. However, there is still a limitation. No cross comparison of all micro criteria under opportunity and challenge is studied. Only the top ranking of the micro criteria under each macro criteria is concluded, but there is no overall top ranking among all micro criteria under opportunity and challenge.

Table 8 - Weighting value - Marco Factor

Criteria	Marco-Factor - Normalization	Final Result
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	Political	Financial	Non-Financial & Altruistic	Internal	Ave Weight	Ranking
Political	1	2.0188	1.0952	1.2460	0.3114	1
Financial	0.4954	1	0.5425	0.6172	0.1543	4
Non-Financial & Altruistic	0.9131	1.8434	1	1.1377	0.2844	2
Internal	0.8026	1.6202	0.8789	1	0.2499	3

Table 9 - Weighting value - Micro Factor: Political

Criteria (Political)	Micro-Factor - Normalization			Final Result	
	O1	O2	O3	Ave Weight	Ranking
O1 - Regulatory Requirements	1	1.5654	1.7155	0.4501	1
O2 - Meeting Green Building Standards	0.6388	1	1.0959	0.2875	2
O3 - GFA Concession	0.5829	0.9125	1	0.2624	3

Table 10 - Weighting value - Micro Factor: Financial

Criteria (Financial)	Micro-Factor – Normalization				Final Result	
	O4	O5	O6	O7	Ave Weight	Ranking
O4 - Cost Saving on Operation & Maintenance	1	1.5771	1.7087	1.7125	0.3567	1
O5 - Price Premium	0.6341	1	1.0835	1.0859	0.2262	2
O6 - Monetary Incentives to Owners	0.5852	0.9230	1	1.0022	0.2088	3
O7 - Monetary Incentives to Professional	0.5839	0.9209	0.9978	1	0.2083	4

Table 11 - Weighting value - Micro Factor: Non-Financial & Altruistic

Criteria (Non-Financial & Altruistic)	Micro-Factor - Normalization			Final Result	
	O8	O9	O10	Ave Weight	Ranking
O8 - Job Opportunities	1	1.2118	1.3555	0.3902	1
O9 - Customized Incentives	0.8252	1	1.1186	0.3220	2
O10 - CSR	0.7377	0.8940	1	0.2878	3

Table 12 - Weighting value - Micro Factor: Internal

Criteria (Internal)	Micro-Factor - Normalization				Final Result	
	O11	O12	O13	O14	Ave Weight	Ranking
O11 - Improve Corporate Reputation	1	1.8190	1.9747	1.7501	0.3806	1
O12 - Long Term Business Competitiveness	0.5498	1	1.0856	0.9622	0.2092	3
O13 - Indoor health & productivity enhancement	0.5064	0.9211	1	0.8863	0.1927	4
O14 - Priority review of green projects	0.5714	1.0393	1.1283	1	0.2175	2

Table 13 - Weighting value - Marco Factor

Criteria	Marco-Factor - Normalization					Final Result	
	Political	Financial	Non-Financial	Internal	Technological	Ave Weight	Ranking
Political	1	1.3021	1.2670	1.2415	1.0578	0.2321	1
Financial	0.7680	1	0.9730	0.9534	0.8124	0.1783	5
Non-Financial	0.7892	1.0277	1	0.9798	0.8349	0.1832	4
Internal	0.8055	1.0489	1.0206	1	0.8521	0.1870	3
Technological	0.9453	1.2309	1.1978	1.1736	1	0.2194	2

Table 14 - Weighting value - Micro Factor: Political

Criteria (Political)	Micro-Factor - Normalization			Final Result	
	C1	C2	C3	Ave Weight	Ranking
C1 - Lack of Government's Promotion	1	2.2891	1.5190	0.4773	1
C2 - Insufficient Incentives	0.4369	1	0.6636	0.2085	3
C3 - Insufficient Public Awareness & Education	0.6583	1.5069	1	0.3142	2

Table 15 - Weighting value - Micro Factor: Financial

Criteria (Financial)	Micro-Factor - Normalization			Final Result	
	C4	C5	C6	Ave Weight	Ranking

C4 - Long Payback Period	1	1.7797	1.1138	0.4066	1
C5 - High Maintenance Costs	0.5619	1	0.6259	0.2284	3
C6 - High Hidden Risk on Costs	0.8978	1.5978	1	0.3650	2

Table 16 - Weighting value - Micro Factor: Non-Financial

Criteria (Non-Financial)	Micro-Factor - Normalization				Final Result	
	C7	C8	C9	C10	Ave Weight	Ranking
C7 - Aging of Existing Building	1	1.0842	1.1268	1.0970	0.2687	1
C8 - High Density	0.9224	1	1.0393	1.0118	0.2479	2
C9 - Comprehensive Use of Lighting and Air-con	0.8875	0.9622	1	0.9735	0.2385	4
C10 - Ignore Water Saving	0.9116	0.9883	1.0272	1	0.2450	3

Table 17 - Weighting value - Micro Factor: Internal

Criteria (Internal)	Micro-Factor - Normalization			Final Result	
	C11	C12	C13	Ave Weight	Ranking
C11 - Lack of Integration among Different Project Parties	1	0.9626	0.8773	0.3146	3
C12 - Hard to Understand BEAM Plus Standards	1.0388	1	0.9113	0.3268	2
C13 - Intricacy on Application	1.1399	1.0973	1	0.3586	1

Table 18 - Weighting value - Micro Factor: Technological

Criteria (Technological)	Micro-Factor - Normalization			Final Result	
	C14	C15	C16	Ave Weight	Ranking
C14 - Lack of Green Building Technologies	1	1.3356	1.3339	0.4003	1
C15 - Lack of Green Building Professionals	0.7487	1	0.9987	0.2997	3
C16 - Insufficient Tech. Skills of Working Levels	0.7497	1.0013	1	0.3001	2

7. Suggested Solutions

After the AHP analysis, quantitative calculation of the questionnaire data and the qualitative measure, face to face interviews, the main challenges faced by the implementation of BEAM Plus are Political factor, followed by technological factor. Due to this reason of important role of government, the HK government should actively promote and facilitate the expansion and development of BEAM Plus. Funding can be given to those developers who have the enthusiasm and thorough proposal in constructing the green building. Regulatory requirement and procedure in applying the standard and the threshold can be relieved in order to attract more investor to invest on it. The HK government can also focus on educating the people about the importance of building a green environment, including the green society and green buildings. Besides, more skilled and experienced workers and professionals can be input from other countries to enhance the knowledge and building technique of the green buildings. The developers can also employ some consultants to give advice and technical solution before the construction stage and to the green construction project started. More hardware, such as building machine, can be introduced and bought in the construction process to improve tackle the technical difficulties. The HK government can also put more resources in education about the training the workers and creating more technical professionals in green project. Since political factor and the meeting regulatory requirements are the most critical factors in motivating others to implement BEAM Plus and other green practice, it is suggested to apply “Carrot and Stick” into the developers or owners side.

In long term, the government shall incorporate the green building practices into the master plan of the city and linkage the percentage of GFA concession with the BEAM Plus rating so developer utilize their capacity to achieve what they can in order to meet the GFA concession instead of just meeting the unclassified level. For those who only meet the unclassified level, punishment such as penalty will be applied. Also, the developer/owners of the building can apply Internet of Things (IoT) into the new buildings. More focused measures are necessary to foster greater awareness among tenants and/or occupants. The government, developers and owners can put more efforts beyond the building structures in green concept and hardware to focus more on end users, which are the tenants and the residents. From the developer/owner side, they can collect the big data from the end-users and which can be a valuable

VOC for developing more constructive measures for green living and improving the products and services that the developer provides. Also, by changing their energy consumption behavior and practices proactively, tenants and occupants can also be part of the solutions rather than the problems. The tenants or occupants can easier to measure the benefits or efforts they have input through IoT. Besides, many professionals from the face to face interview pointed out that the BEAM Plus standard is too complicated to understand and the criteria are not all relevant to HK situation. The Council should simplify the standard for the stakeholders easier to understand and follow and need to review all the criteria from time to time to make sure the tool is capable in HK. Lacking of public awareness is also the key reason of the low demand of the green building. Therefore, promoting the benefits of the green building and conducting more promotion campaign to the public are critical task for HK government.

8. Conclusion

This paper aims at studying the opportunity and challenge of implementation of BEAM Plus in HK through a thorough research of literature review, AHP analysis and structured interview. Having a comprehensive study of literature, research paper and report, we conclude numbers of opportunities and challenges of implementation of green practice. By using the AHP analysis and quantitative calculation, under the macro level, the top two opportunities are Political factor and Altruistic factor. It implies the government is really acting an indispensable role in affecting the growth of BEAM Plus and green project. Job opportunity is also another element and motivator that BEAM Plus could bring to the society. On the other hand, the top challenges are Political factor and Technological factor under the macro level. Without the help of government, it is hard for BEAM Plus to be succeeded. Technical difficulties, such as lack of skills labor and sophisticated machine, are also the obstacle hindering the development of BEAM Plus. Under the micro level, the top opportunity under Political factor is “Meeting regulatory requirements”. Ease of procedure and regulation would be a greater motivation of BEAM Plus implementation. Besides, the top opportunity under Non-Financial & Altruistic factor is “Job opportunities created to the society”. On the other hand, the top challenge under Political factor is “Lack of Government’s Promotion”. The last but not the least, top challenge under Technological factor is “Lack of green building technologies”. It shows the essential and importance of government’s policy and the experts and professionals.

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Key success factors for implementing modular integrated construction projects - A literature mining approach

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Abstract

Modular integrated construction (MiC) is an innovative construction method where components of a building are manufactured in an offsite factory, trucked to the job site in sections, set in place with cranes, and assembled together to form a whole building. Where circumstances merit, favorable conditions exist and implemented effectively; MiC improves project performance. However, several key factors need to converge during implementation to realize the full benefits of MiC. Thus, a thorough understanding of the factors which are critical to the success of MiC projects is imperative. Drawing on a systematic review of 47 empirical studies, this research identified 25 key success factors (KSFs) for MiC projects. Of these, the five topmost cited KSFs for MiC projects include *effective working collaboration and communication among project participants; standardization, optimization, automation and benchmarking of best practices; effective supply chain management; early design freeze and completion; and efficient procurement method and contracting*. The study further proposed a conceptual model of the KSFs, highlighting the interdependences of people, processes, and technology-related KSFs for the effective accomplishment of MiC projects. The set of KSFs is practically relevant as they constitute a checklist of items for management to address and deal with during the planning and execution of MiC projects. They also provide a useful basis for future empirical studies tailored towards measuring the performance and success of MiC projects. MiC project participants and stakeholders will find this research useful in reducing failure risks and achieving more desired performance outcomes. One potential impact of the study is that it may inform, guide, and improve the successful implementation of MiC projects in the construction industry. However, the rigor of the analysis and relative importance ranking of the KSFs were limited due to the absence of data.

Keywords: conceptual model, key success factors, modular integrated construction, review

1. INTRODUCTION

There is a global recognition that the ill-performances of the traditional construction approach engender significant threat and risks to the realization of a sustainable future of modern society and the construction industry [1]. Poor performances abound and some include lower productivity rates [2], schedule and budget overruns [3], quality problems, higher construction waste, carbon emissions [4], shortage of labor force, and the poor state of worker's health and safety [5]. However, the aggregate documentation of these ill-performances of the sector in the global context has the tendency of masking the significant regional and national differences in the magnitude of the challenges confronted [6]. Notably, the impacts of these challenges are multiplied in economies such as the Hong Kong Special Administrative Region (hereafter Hong Kong). Hong Kong is an iconic high-density metropolis with scarce developable land which drives the development of high-rise buildings. The construction sector of Hong Kong has the 2nd most expensive cost of construction in the world [3], generates a huge proportion of landfill wastes [7], and draws heavily on local labor force which is undergoing rapid

aging. These collectively present a huge threat to the sustainable future of Hong Kong and the construction industry. Consistent with global transition towards industrializing and revolutionizing the construction sector [8], the Hong Kong SAR Government initiated modular integrated construction (MiC) within the Policy Addresses 2017 and 2018 as a strategic policy initiative towards enhancing innovative construction, productivity improvement, and meeting the requirements of high-rise high-density building construction in Hong Kong [9].

MiC is an innovative construction method which transforms the fragmented site-based construction of buildings into an integrated production and assembly of value-added factory-made prefabricated prefinished volumetric modules [6,9]. Drawing on the concepts of modularity, modularization, industrialized production, and lean construction, MiC represents the most complete form of off-site construction (OSC) with the greatest integration of value-added prefinished volumetric modules where 80-90% of a whole building can be completed in an offsite factory [10,11]. MiC belongs to a family of OSC techniques such as prefabricated prefinished volumetric construction, modular construction, industrialized housing construction, PPMOF (prefabricated, preassembly, modularization, and off-site fabrication), industrialized building systems, off-site manufacture, modern methods of construction, prework and off-site production [6,8,11]. Experiences with these techniques in Singapore, Canada, China, Sweden, Switzerland, New Zealand, USA, UK, Malaysia, Australia, and Japan established that achievable benefits of MiC include shortened construction time, improved working environment and site safety, improved sustainability and environmental performance, high construction quality, better management, and reduced lifecycle cost [9,12].

Despite these promises, the feasibility of employing MiC for high-rise building construction in Hong Kong currently remains cloudy [9]. Hong Kong is at the earliest stage of the MiC learning curve with few pilot projects been initiated and yet to be completed. However, MiC is associated with a unique supply chain, complex network of stakeholders, engineering, and management requirement different from those of the traditional construction approach. This means that best practices in traditional construction project management might not be directly applicable to MiC projects. As expected, countries continue to struggle with the implementation of MiC and evidences indicate that not all executed projects resulted in desirable project performance. Notwithstanding some failures, MiC projects have been successfully implemented in other countries, but an understanding of the KSFs is lacking. Such understanding is imperative in reconciling the implementation and management of MiC projects with the reality that a significant number of MiC projects do not currently succeed.

Considering that MiC has gained significant attention, a deeper understanding of the KSFs for implementing its projects is imperative. Choi et al. [13] echoed that improved understanding and prioritization of the KSFs for MiC project planning and implementation is imperative to achieve higher success. As KSFs are the few vital management areas that must receive sustained attention and commitment to ensure success [14] of MiC projects, this review study seeks to (i) identify, summarize and integrate the KSFs for MiC projects, (ii) examine the most cited KSFs for MiC projects, and (iii) propose a conceptual model of the KSFs for MiC mapping their interactions and interdependences. The output of this research is timely and relevant to Hong Kong and other countries as the construction industries attempt to benchmark best practices along the MiC learning curve. By drawing on lessons from multiple MiC project types, sizes, phases, purposes, characteristics, and environments in different countries, the framework of the KSFs forms a useful basis for future empirical studies on MiC KSFs.

2. RESEARCH METHOD AND APPROACH

This research draws on a systematic literature review methodology and systems dynamic modelling approach to examine the KSFs for implementing MiC projects. Figure 1 is a schematic of the methodological framework of the study. The study adopted a systematic review approach because it is a useful methodology for establishing the start of the art scientific knowledge of a given subject [6]. It is an established research methodology which draws on published and grey literature to delineate boundaries of existing knowledge, provide a basis for theory development and guides evidence-based policy formulation [8]. It offers an integrated perspective of scientific evidence on a given subject and brings the scientific literature closer to industry and policy decision-making. For this, it is widely used in many disciplines including the construction engineering and management research domain [6,8,15]. The systematic review was implemented based on a three stage methodological framework of literature retrieval and analysis, metadatabase extraction and identification of the KSFs (see Figure 1). The literature

analysis started with selection of suitable keywords and literature search. Thus, the primary synonyms for key success factors and modular integrated construction used in the literature were identified. The implemented sets of keywords for the two phrases are shown in Table 1. These keywords were selected because they constitute the most commonly used interchangeable terminologies for MiC and KSFs in the literature. Indeed, the keywords were updated throughout the study period. These keywords were used to retrieve articles which addressed KSFs for any of the listed models of MiC. Using the keywords, structured and constrained queries were executed in Scopus and Web of Science; the two most commonly used literature databases in construction engineering and management (CEM) review studies [15].

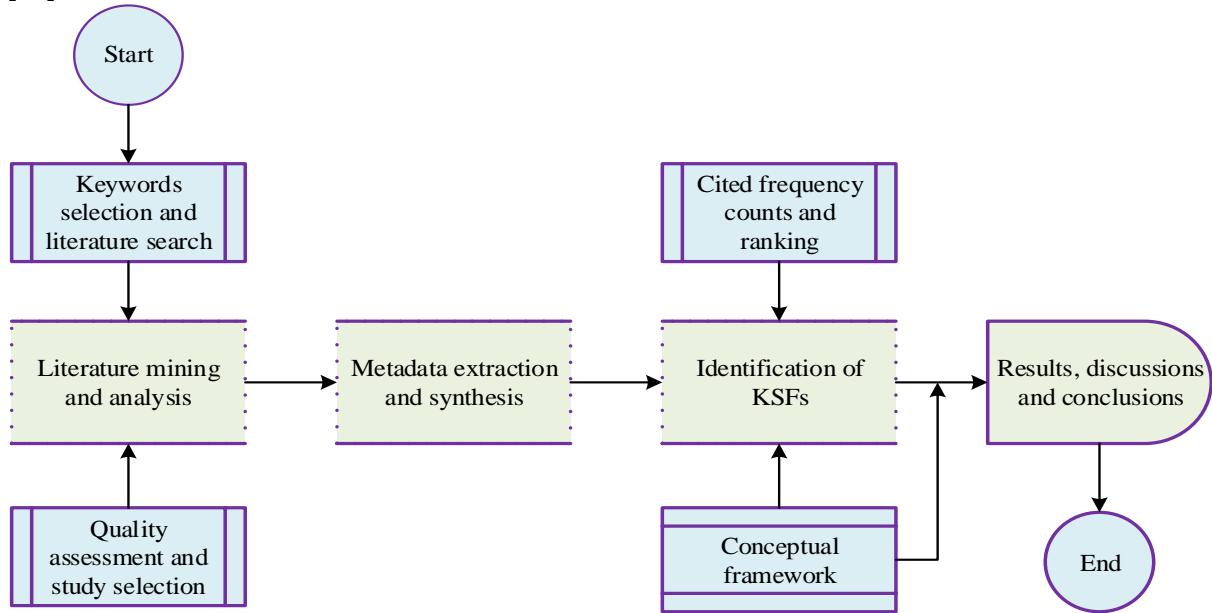


Figure 1. Methodological framework for the study

These literature search engines were selected because they index a wider spectrum of research articles within the CEM research domain [6,15]. Their wider adoption CEM systematic reviews stem from the associated higher degree of repeatability and verifiability of the search results. Using the fuzzy Boolean connector “AND”, the authors search for studies containing a combination of at least one keyword each from the first and second set of keywords. No year range was defined but the language of studies was restricted to English. The authors also restricted the literature to journal articles and conference papers only. These restrictions filtered and generated 53 Scopus records (as of 4 June 2019). The authors conducted rapid screening of the titles and abstracts of these records and 30 were found to be relevant to the study.

Table 1. List of keywords used in the literature search and retrieval

Terminology	List of keywords
Key success factors (KSFs)	<i>Critical success factors; success factors; critical factors; few key areas; key results areas; decision support factors</i>
Fuzzy Boolean concatenator	<i>AND</i>
Modular integrated construction (MiC)	<i>Modular integrated construction; off-site construction; off-site production; off-site manufacture; prefabrication; prefabricated; industrialized building system; modular construction; industrialized construction; prework; industrialized housing construction; prefabricated prefinished volumetric construction; modular volumetric construction</i>

Although this sample is small but considering that MiC is relatively new, the figure indicates that researchers and practitioners are becoming interested in KSFs, highlighting the relevance of this study.

These studies were downloaded for full-text evaluation. However, the authors further conducted a general *Google* search to retrieve relevant industry reports, books and theses on the KSFs for MiC. This resulted in the retrieval of 25 relevant documents, which were also downloaded for full-text evaluation. During the full-text evaluation, articles were included if they involved empirical studies on the KSFs for MiC and thus, review articles and editorial notes were excluded. The research designs and methodologies for each study were evaluated to ascertain their overall quality and further justification for inclusion. This criterion was relaxed when considering the industry reports. After the full-text evaluation, 47 studies were found to be relevant to the aim of the study. For each study, the authors extracted the reported KSFs and recorded them in a summary table created in Excel. The number of times a KSF was reported or cited was catalogued and used as a basis for ranking the KSFs in the study. This ranking approach has been adopted in previous studies [6].

3. REVIEW FINDINGS AND DISCUSSIONS

3.1. Summary of the Included Studies

The paper synthesized research evidence from 47 empirical studies on the KSFs for MiC. The included studies comprised 32 journal articles, 7 conference papers, 7 industry reports, and 1 Ph.D. thesis. These studies were conducted in the United States (15), United Kingdom (8), Canada (5), Malaysia (4), Hong Kong (4), Australia (3), Sweden (2), China (1), Japan (1), Singapore (1), Nigeria (1), South Korea (1), and Turkey (1). These countries have some of the most successful MiC projects [8] and thus, offered useful basis for deciphering distilling information on the KSFs for MiC projects. These studies investigated the KSFs across a range of MiC project types including power plant projects, petrochemical plant projects, industrial plant projects, chemical plant projects, schools, residential building projects, and multiple projects. Thus, the sample is adequate to establish a comprehensive perspective of the KSFs for implementing MiC projects.

3.2. Evaluation and ranking of the KSFs for Implementing MiC Projects

The analysis of the 47 documents resulted in the extraction of 45 KSFs for MiC projects of which 20 were each cited once in the included studies and thus, excluded in the analysis. Table 2 shows a summary of the 25 most cited KSFs for implementing MiC, their citing sources, cited frequency counts and relative frequency ranking. Although the KSFs for MiC are sensitive to project types, project sizes, environment, and territories [13], these sets of KSFs were shared among projects and countries and thus, constitute a common framework of the KSFs for MiC projects. The number of studies which cited a KSF was computed as its cited frequency count and used to rank the KSFs in this research. The authors immediately recognize that ranking of the KSFs based on frequency counts could be misleading, but such approach is recommended and used when quantitative meta-analysis is not feasible [6]. The five most cited KSFs for MiC projects include *effective working collaboration and communication among project participants; standardization and benchmarking of best practices; effective supply chain coordination and management; early design freeze and completion; and suitable procurement method and contracting*. Due to space constraints, these 4 most cited KSFs are briefly discussed.

3.2.1. Effective working collaboration and communication among project participants

This KSF has been cited in 12 of the 47 studies and ranked 1st among the 25 shortlisted KSFs. Irrespective of project type and territory, MiC projects require the commitment of multiple participants and stakeholders, who have their unique goals, value systems and expectations in the project [6]. Thus, the success of MiC projects is a function of effective collaboration, information sharing, and communication among the project participants [16]. For instance, effective communication between project owners and the design team is crucial at the conceptual design stage to allow for early decision to implement MiC. There is the need for information sharing and collaboration between the design team (designer, architect, structural engineer) and fabricators or manufacturers to allow for a more precise understanding of the detailed working drawings to reduce dimensional tolerances [17]. The collaboration and communication among project participants is a necessary recipe for minimizing delays, conflicts, geometric variabilities, and reworks [6,11].

3.2.2. Standardization, optimization, automation and benchmarking of best practices

This factor ranked 2nd among the 25 shortlisted KSFs and was cited in 11 studies. Standardization is the process of implementing and developing technical standards based on the consensus of various stakeholders of MiC projects. Standardization reduces the tendency of producing unique modules to meet the specification of every implemented MiC project. It facilitates optimization and improved automation of the MiC process [18]. Warszawski [19] concurred that standardization allows for efficient allocation of resources and increases the benefits of specialization of labor in MiC projects. Through benchmarking best practices, the performance and success of MiC project can be reliably predicted based on relevant indicators and management practices. Through standardization, the production process, equipment, and labor skills can be adapted to meet the demands of the MiC project.

Table 2. Ranking of the key Success factors for implementing MiC Project

#	Key success factors	Sources	Frequency	Rank
1	Effective working collaboration and communication among project participants	[13,16,17–24, 25]	12	1
2	Standardization, optimization, automation and benchmarking of best practices	[18,19,37,29–36]	11	2
3	Effective supply chain management	[21,22,24,38–44]	10	3
4	Early design freeze and completion	[18,19,22,30,32–37]	10	3
5	Efficient procurement method and contracting	[22,28,29,31,41,44,45]	7	5
6	Early and continuous engagement of project participants throughout the project	[22,23,32,33,37,45,46]	7	5
7	Early and effective use of information technology	[22,24,25,43,47–49]	7	5
8	Adequate knowledge and experience of relevant players	[13,25,29,31,41,50,51]	7	5
9	Extensive and effective project planning, scheduling and implementation	[21,22,24,26,41,52]	6	9
10	Effective risk management	[13,22,43,50,51,53]	6	9
11	Early definition of project scope and budget	[13,20,21,26,44,51]	6	9
12	Capability and experience of modules fabricator (s)	[13,34,50,51,53,54]	6	9
13	Adequate transport infrastructure and modular installation equipment	[13,34,50,51,53,55]	6	9
14	Early advice from MiC design professionals	[27,36,53,56,57]	5	14
15	Top-management support, commitment, and involvement in the supply chain	[20,27,34,55]	4	15
16	Early involvement of fabricator	[13,50,51,53]	4	15
17	Systematic economic analysis and early decisions	[21,26,41,58]	4	15
18	Avoidance of owner delays	[13,50,51,53]	4	15
19	Module envelope limitation	[13,50,51,53]	4	15
20	Reasonable lead time to allow for prototyping and trials	[31,59]	2	20
21	Efficient logistical services	[53,60]	2	20
22	Effective coordination of on-site and off-site activities	[31,46]	2	20
23	Design compliance with relevant codes, procedures, and efficient statutory verification	[46,61]	2	20
24	Effective management of dimensional tolerances	[17,62]	2	20
25	Adequate modular design codes, specification and regulations	[46,61]	2	20

3.2.3. Effective supply chain management

MiC is associated with a complex supply chain and stages to be coordinated and managed. Effective supply chain management ranked 3rd among the 25 shortlisted KSFs and was cited in 10 empirical studies. The MiC supply chain can be reified as modular design, engineering, production, transportation, and on-site assembly. These stages are fragmented but interdependent within the supply chain. Disturbances in the upstream segments could compromise the performance of downstream supply chain segments [6]. For instance, timely delivery of modules to the site is required for continuity of the project and this also depends on the reliability of the off-site modular production and logistics efficiency. Thus, effective coordination and management of the supply chain segments, the associated stakeholders and events are critical for the success of MiC projects, irrespective of project type or territory [6,11].

3.2.4. Early design freeze and completion

This KSF was cited in 10 empirical studies and ranked 3rd among the 25 shortlisted KSFs. Considering the current lower level of standardization, each MiC project requires separate design and production of specific modules to be used in any project. Therefore, early design freeze is required prior to the fabrication and production of the modules [33]. This stage is critical because all the major downstream supply chain stages depend on the timely design freeze. Subsequent changes to the design could engender significant risk to the time and schedule of the MiC project [6,11]. Thus, developers, owners, and housing authorities need to give due consideration to this KSF to realize the time savings benefits of the MiC approach.

3.3. Conceptual Model of the KSFs for Implementing MiC Projects

To facilitate a better understanding of the nature of the KSFs for implementing MiC projects, it is useful to represent the shortlisted KSFs in a conceptual model highlighting their clusters and interactions. Following a detailed evaluation of the 25 KSFs, it is found that each KSF is associated with people (stakeholders), process (supply chain) or technology.

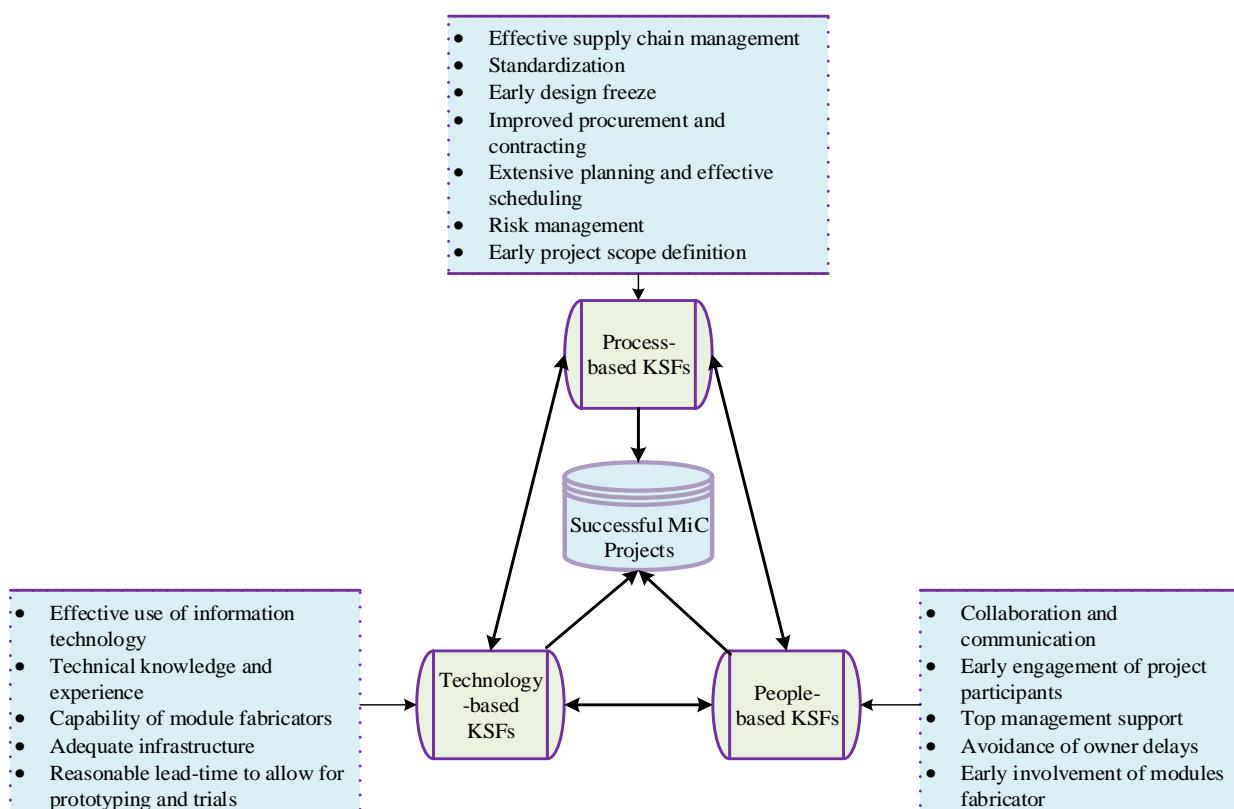


Figure 2. Conceptual model of the key success factors for MiC Projects

Although some KSFs could be well-placed under two or all these components, the authors have allocated each KSF to one cluster to facilitate improved understanding of the nature of each KSF. Figure 2 is a conceptual model showing the interactions among the people, process, and technology-related KSFs for implementing MiC projects. It is useful to highlight the complimentary KSFs because it will allow for the strategic allocation of resources to achieve a competitive advantage. It also highlights the key interactive results areas which could be prioritized to reap the benefits of other KSFs. Figure 2 shows that there are interdependencies among the people, technology and process-related KSFs. For instance, the effective use of technology such as building information modeling improves collaboration and communication among project participants [49] and facilitates the coordination and management of the MiC supply chain and associated risks [49,63]. Additionally, early engagement of participants would facilitate early design completion and freeze [33]. Early involvement of the modules fabricator could significantly reduce risk of dimensional and geometric tolerances [17,62]. Among the process KSFs, standardization improves supply chain management through reduction of the need to fabricate unique modules for each MiC project [18,19]. Among the people KSFs, top management support is required to allow for early engagement of relevant project participants in the conceptual design, planning and construction stages [27].

4. CONCLUSION AND FUTURE RESEARCH

If effectively implemented, MiC shortens construction time, improves working environment & site safety, offers improved sustainability & cleaner construction process, generate high construction quality and better management. However, several key management factors need to converge to realize the full benefits of MiC. Considering that MiC is fledgling in some economies such as Hong Kong, the construction industry can benefit from a thorough understanding of the factors which are critical to the success of MiC projects. Despite some casualties, MiC projects have been successfully implemented elsewhere. However, the KSFs for implementing MiC projects are yet to be reviewed and modelled. This research identified, summarized and integrated the KSFs for implementing MiC projects through the lens of systematic review methodology. Drawing on a sample of 47 empirical studies, the study synthesized 25 KSFs for MiC projects. Of these, the top 5 most cited KSFs are *effective working collaboration and communication among project participants; standardization, optimization, automation and benchmarking of best practices; effective supply chain management; early design freeze and completion; and efficient procurement method and contracting*. The study further proposed a conceptual model of the KSFs highlighting their interdependences in the implementation of MiC projects. Although the appropriateness of the KSFs in any context was not verified, the set of KSFs are practically relevant as they constitute a checklist of items for management to address and deal with during the planning and execution of MiC projects. The common framework of the KSFs develop would provide a useful basis for future empirical studies on the KSFs for implementing MiC. One potential impact of the study is that it may inform, guide and improve the successful implementation of MiC projects in the construction industry. However, the rigor of the analysis, relative importance ranking and systems dynamic modelling of the KSFs were limited due to the absence of empirical data. Future empirical research will (i) quantitatively evaluate and rank the KSFs using primary industry data, (ii) identify the key success processes for the KSFs, (iii) quantitatively assess and establish the interactions among the KSFs, and (iv) develop MiC project success model based on a multi-criteria decision analysis.

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Issues of New Technological Trends in Nuclear Power Plant (NPPs) for Standardized Breakdown Structure

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Abstract: Recent efforts to develop a common standard for nuclear power plants (NPPs) with the aim of creating (1) a digital environment for a better understanding of NPPs life-cycle management aspect and (2) engineering data interoperability by using existing standards among different unspecified project participants (e.g., owners/operators, engineers, contractors, equipment suppliers) during plants' life cycle process (EPC, O&M, and decommissioning). In order to meet this goal, there is a need for formulating a standardized high-level physical breakdown structure (PBS) for NPPs project management office (PMO). However, high-level PBS must be comprehensive enough and able to represent the different types of plants and the new trends of technologies in the industry. This has triggered the need for addressing the issues of the recent operational NPPs and future technologies' ramification for evaluating the changes in the NPPs physical components in terms of structure, system, and component (SSC) configuration. In this context, this ongoing study examines the recent conventional NPPs and technological trends in the development of future NPPs facilities. New reactor models regarding the overlap of variant issues of nuclear technology were explored. Finally, issues on PBS for project management are explored by the examination of the configuration of NPPs primary system. The primary systems' configuration of different reactor models is assessed in order to clarify the need for analyzing the new trends in nuclear technology and to formulate a common high-level PBS. Findings and implications are discussed for further studies.

Key words: nuclear power plants (NPPs), project management organization (PMO), physical breakdown structure (PBS), reactor model (RM), reactor coolant system (RCS)

1. INTRODUCTION

While the world's nuclear power generation is expected to increase in the coming decades, the nuclear power plant construction market is also growing, and there is a need for creating an international standard for nuclear digital environment. In order to develop a common set of rules or standards for the digital ecosystem of NPPs with the intention of addressing (i) NPPs life-cycle management aspects amongst different project participants (e.g., owners/operators, engineers contractors, equipment vendors), plant life cycle process (EPC, O&M, and Decommissioning), and multiple value chain, (ii) issues to digitally exchange NPPs information handover from EPC to O&M and then to decommissioning, (iii) life cycle engineering data interoperability by using existing international standards (e.g., ISO 15926, 10303, CFIHOS). For this purpose, it is crucial to understand the recent conventional NPPs and global trends in the radical transformation of future reactors to compare the changes in the plant's physical asset in terms of structure, system, and components (SSC), as well as plant configuration.

The physical component of a plant facility with respect to the project management organization (PMO) of owners/operators and contractors has intrinsic values and is used as a project scoping mechanism for different project management practices, including but not limited to project performance management and life-cycle information management [1]. Project managers use different practical methodologies for defining an organized set of physical components of a plant facility, and physical breakdown structure (PBS) is one of the techniques. Although the term PBS has been defined in a

number of ways, PBS is a hierarchically organized set of project physical components with combined entities of project administration activity, incorporating different aspects of project deliverables, in the context of this study. As in other projects, PBS in the NPPs project consists of different leveled asset entities or SSC together with NPP managerial aspects in a top-down course of action.

In order to formulate a common standardized high-level candidate entity for a common PBS, representing recent plants and advanced reactors of the future, it is vital to analyze different trends in nuclear technology in the nuclear plant facility. This ongoing research examines the different types of nuclear plants, interrelated technological trends in reactor advancement, and the gradual changes in the power plant's reactor system. The recent reactor model types with the perspective of new trends are explored. Finally, the need for exploring nuclear power technology to formulate a standardized PBS by examining the configuration of the primary system, which contains the reactor system of different reactors as an example, is discussed.

This study is organized in a four-step research framework as shown in Figure 1. The four steps include: (1) an extended classification of NPPs identified based on the previous research of the authors [2], (2) new trends of technological changes in the developed reactor analyzed through literature review, (3) different reactor models regarding interrelated new trends, (4) assessing the primary systems configuration of different reactor models in order to clarify the need for analyzing the new trends in nuclear technology and to formulate a common PBS.

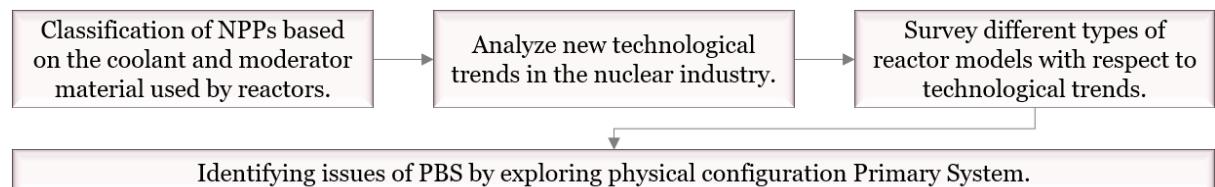


Figure 1. Research Design

2. CLASSIFICATION AND STATUS OF NUCLEAR POWER PLANT (NPPs)

The primary system of any NPPs, containing the reactor coolant system (RCS) and reactor system (RS), is the critical system that determines the plant efficiency and overall plant configuration, as well as commissioning process. There are over 86 reactor models in the world, which are classified from a previous research by the authors, under eight power plants based on the type of coolant and moderator materials the RCS uses [2], as shown in Figure 2. Hence, the coolant and moderator materials determine a specific power reactor type.

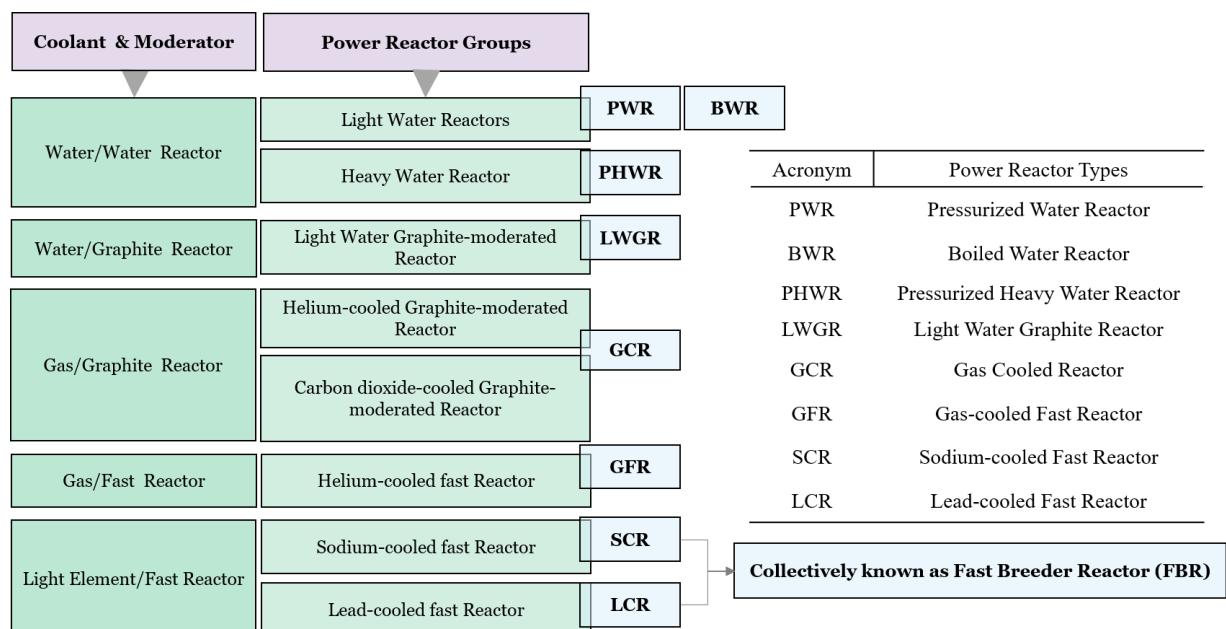


Figure 2. Classification of power plants based on coolant and moderator materials

According to the International Atomic Energy Association (IAEA) nuclear power reactor information system [3], as of August 2020, the record shows that 439 NPPs are currently operational, and 52 plants are under construction all around the globe. Pressurized Water Reactor (PWR) is one of the most used power plant types followed by boiling water reactor (BWR), pressurized heavy water reactors (PHWR), and light water gas cooled reactors (LWGR), respectively. With over 65% all operational plants and 85% of plants under construction PWR recently integrates more advanced features.

The plants that are under construction use variants of advanced reactors, with an increase in the number of new technologies being seen. The new reactor models are designed for self-reliance and use less complicated design features. Since the late 2000s, the reactor models that are being commissioned for NPPs mostly fall under the new variants, generation III, III+, IV, and small modular reactors (SMRs) of interrelated technologies; for example, System-integrated Modular Advanced Reactor Technology (SMART) is a small-sized, modularized, fast, and integrated pressurized water reactor.

The global growth of nuclear power energy slowed during the 2008 global economic recession. After the Fukushima-Daiichi nuclear accident, a radical change in the design innovation of NPP's structure, system, component (SSC) triggered countries to improve their long-existing conventional plants to a safer, optimized, and economical version [4,5]. Due to facing greater project complexity and demands for higher safety requirements, the NPPs industry continually seeks ways to improve plant performance through alternative advanced nuclear energy systems. By adopting advanced design features based on the self-reliant technologies, the early 2010s has been the period of developing an advanced nuclear reactor and has projected a minimum of 40% increase in nuclear power production by 2035 [4]. Among the promising directions for NPP technological development is the introduction of less complex smaller units that are more affordable, using fast reactors with enhanced safety systems, as well as plants that can operate up to 60 years as discussed in Section 3.

3. TECHNOLOGICAL CHANGE IN NUCLEAR POWER PLANTS (NPPs)

Based on the objective above, reactor design changes greatly affect the physical configuration especially the reactor system and additional facilities depending on the operational purposes of the plant. Major configuration changes are occurring in the plant's structure, reactor system, power production systems, and auxiliary systems. However, there is a slight lower-level difference between the balance of plant systems (electrical system, HVAC system, instrumentation, and control system). The key concerns for alternative nuclear technologies are, but not limited to, the need for: standardized design and reduction in capital and life cycle cost, optimized construction duration, easy operability and less vulnerability to accidents, minimum nuclear waste, and advanced passive safety system [6,7]. NPPs technological ramification can be manifested by four interrelated technological trends as illustrated in Figure 3.

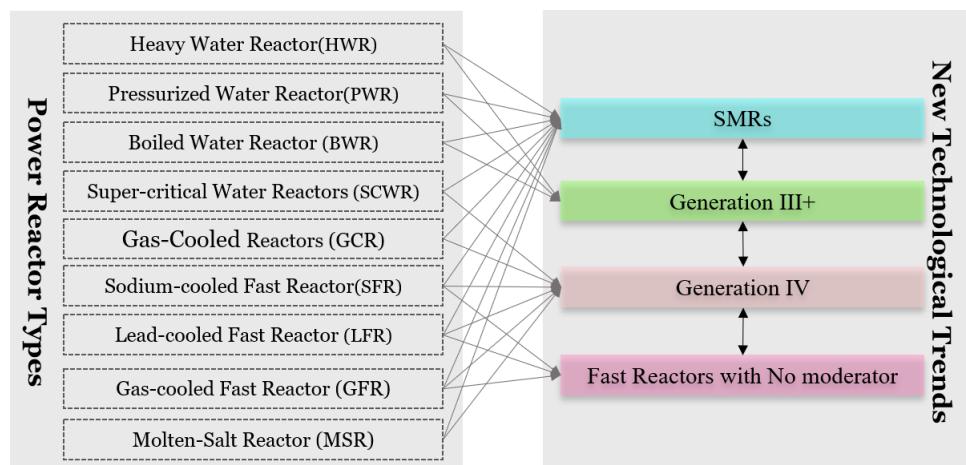


Figure 3. Classification of power plants based on coolant and moderator materials

Generation III+ reactor models, currently under deployment by different countries with a growing number of plants under construction, is the future of NPPs [4,8]. Generation III+ reactors are evolutionary extension from Generations II and III of pressurized water reactors (PWR), boiled water

reactors (BWR), and PHWR designs with some radical changes, including advanced safety features without any control equipment.

International collaboration is organized to develop future advanced nuclear reactor energy systems and form the Generation IV International Forum (GIF). GIF's effort contributes to the advancement of multi-purpose reactors (hydrogen production, water desalination, and other commercial operations) [4]. GIF is based on six reactors (GFR, LFR, SFR, molten salt reactors [MSR], supercritical water-cooled reactors [SCWR], and very high-temperature reactor [VHTR]). However, the actual deployment of GIF reactors is expected to happen in the coming decades.

An important manifestation of new development activities in the area of nuclear plant design is the widespread interest in small plants incorporating passive, rather than active, safety features and simplified systems design. The small plant may be the best choice for applications on a relatively small grid or when load growth rate is expected to be low on a large grid. The concept of Small Modular Reactors (SMR) can be manifested either by small, medium-sized, or modular reactors with a power outage of 300MWe per module. SMRs are based on a small-scale version of existing-generation II & III reactor designs, to entirely new advanced generation III+/IV by means of modular-based reactor designs [5,6]. The majority of SMRs are from conventional light water reactors. However, there has been a growing number of generation IV small scaled test reactor recently as shown in Table 1. When conventional reactor models are compared, SMRs can offer a significant benefit because of the size, modularity, and simplicity of the design, as well as its advantages of scalability, flexibility, deployment ability, optimized economics, and passive safety approaches. The small-scaled plants have a less complicated structure and system configurations in which sub-systems are confined into a single system, unlike previous conventional reactor designs.

Fast-Reactors, offering optimized usage of nuclear fuel, fast reactors have no moderator materials [9]. Due to its operational characteristics, fast reactors are cooled by liquid metals, usually sodium and lead metal. Different technological programs have been improving sodium-cooled Fast Reactor (SFR) and Lead-cooled Fast Reactor (LFR), collectively known as fast breeder reactors (FBR) [8]. In some countries, fast-reactor development activities are performed within the framework of the GIF.

It is becoming increasingly clear that safety and economics are the driving issues for reactor advancement and a reactor which is built and operated to high safety standards tends to be a reliable reactor which is economically viable. An overlap of the above-mentioned new reactor trends is shown in Figure 4.

Generation IV Reactors									
Generation III+ Reactors					Fast Reactors				
PWR	BWR	HWR	GCR	iPWR	SCWR	MSR	GFR	LFR	SFR
AP 1000	ABWR	ACR-1000	GTHTR300C	IMR	CSR1000	IMSR-400	ALLEGRO	ALFRED	4S
AP-600	ABWR-II	AHWR	HTR-PM	NuScale	HP-LWR	LFTR	EM2	BREST-OD-300	ASTRID
APR+	BWRX-300	EC6	PBMR	SMART	JSCWR	Mk1 PB-FHR	KAMADO FBR	CLEAR-I	BN-1200
APR1000	ESBWR	IPHWR-220	Prismatic HTR			MSFR		ELECTRA	CFR-600
APR1400	KERENA	IPHWR-700	SC-HTGR			MSR-FUJI		ELFR	FBR-1 & 2
APWR	RMWR					MSTW		G4M	JSFR
ATMEA1						SmAHTR		LFR-AS-200	MBIR
EPR						ThorCon		MYRRHA	PGSFR
FBNR								PEACER	PRISM
HAPPY200								SEALER	TWR-P
KLT-40S								SVBR-100	
NUWARD								W-LFR	

❖ iPWR & SCWR are advanced pressurized water reactors (PWR), ● SMRs

Figure 4. Trends and Interrelations of future reactor models (Reorganized by using data from [3])

4. PBS FORMULATING ISSUES FOR PROJECT MANAGEMENT

In the context of NPPs, PBS is a structured representation in a top-down manner of a nuclear plant facility's physical and managerial scopes. The first level of a PBS in a nuclear facility indicates the managerial aspect, which relates to the tasks or work category. In addition, the first level includes plants' structural and architectural systems (nuclear reactor system, turbine-generator, auxiliary), as well as balance of plant system (electrical system, HVAC systems, instrumentation, and control) entities.

Nuclear power plant structural facilities are mainly composed of nuclear island (RCB), auxiliary building (AUX), turbine island (TUB), radwaste building (RWB), control building (COB), yard structure (YARD), hydrogen production facility, and site improvements (SITE). In the case of new reactors, some of the structures are combined in a single structure. In the case of molten salt reactor, RCB and TUB are confined in a single structure, while SFRs AUX, TUB, and RCB are combined in a single facility [2].

However, among the first-level entities, the primary system which contains the reactor coolant system (RCS), manifest a variant of plant configuration with respect to the reactor model type and inclusive of new trends of technology. RCS provides reactor cooling by transferring the heat from the core to the secondary system to produce steam for the turbine. The major components of the RCS consist of a reactor vessel (RV), steam generators (SGs), reactor coolant pumps (RCPs), pressurizer, pressurizer relief tank (PRT), reactor coolant pipes, and valves. Primary system configuration is different based on the power reactor types and related technological trends as shown in Table 1.

Similarly, the RCS systems and structures of a power plant have different types of configuration according to the type of reactor model. In order to formulate a comprehensive PBS, it is vital to assess the new trends of technologies in the industry.

There is a high possibility of formulating a high-level entity for a common standardized PBS with a high comparative capability of different types of NPPs.

Table 1. An example of primary system configuration

Power reactor type	Reactor model name	New trends	Primary system configuration
PWR	SMART	Generation IV SMR	All major primary components, such as core, steam generators, pressurizer, control element drive mechanisms, and main coolant pumps, are installed in a single reactor pressure vessel [8].
	CAREM	Generation III+ SMR	The entire high energy primary system-core, steam generators, primary coolant, and steam dome is contained inside a single reactor pressure vessel [8].
	ESBWR	Generation III+	The technology uses natural circulation for coolant recirculation within a reactor pressure vessel; therefore, there are no recirculation pumps and none of the associated piping, power supplies, heat exchangers, and instrumentation and controls [10].
BWR	HTGR	Generation IV SMR	Instead of RCS, there is an intermediate heat exchanger (IHX) that transfers the heat from the reactor vessel to the turbines [11].
	PRISM	Generation IV SMR	Unlike PWRs, the RCS is kept within the reactor vessel which also encompasses IHX [12].
SFR		Fast-Reactor	

5. CONCLUSION

This study was intended to provide a comprehensive summary on the changing of NPPs' reactor technologies and new trends of reactors in order to formulate a standardized high-level PBS for owners/operators of PMO. Therefore, this paper presented a short overview of trends in the development of new NPPs, which primarily depended on the reactor model technologies. Relative to the current conventional NPPs technologies, the claimed benefits of the new trends included improved safety systems, longer plant life, easy deployment, and optimized plant performance. To this day, these diverse new issues have been manifested by four variants of new global trends of nuclear technology: generation III+, generation IV, SMRs, and fast reactors, as discussed in Section 3. In addition, the new reactor models were explored regarding the new technologies. Finally, an overview of NPPs' primary system configuration in different reactor models were discussed in order to show how it is necessary to analyze conventional reactors and future technological trends in order to formulate a standardized high-level physical breakdown structure. Future works will explore the SSC configuration of selected reactor models from every reactor type in order to come up with a common entity for a high-level PBS for owners/operators of PMO.

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XV. BIG DATA AND AI LEARNING I (E3)

Combining Machine Learning Techniques with Terrestrial Laser Scanning for Automatic Building Material Recognition

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Abstract: Automatic building material recognition has been a popular research interest over the past decade because it is useful for construction management and facility management. Currently, the extensively used methods for automatic material recognition are mainly based on 2D images. A terrestrial laser scanner (TLS) with a built-in camera can generate a set of coloured laser scan data that contains not only the visual features of building materials but also other attributes such as material reflectance and surface roughness. With more characteristics provided, laser scan data have the potential to improve the accuracy of building material recognition. Therefore, this research aims to develop a TLS-based building material recognition method by combining machine learning techniques. The developed method uses material reflectance, HSV colour values, and surface roughness as the features for material recognition. A database containing the laser scan data of common building materials was created and used for model training and validation with machine learning techniques. Different machine learning algorithms were compared, and the best algorithm showed an average recognition accuracy of 96.5%, which demonstrated the feasibility of the developed method.

Key words: Material recognition, Terrestrial laser scanner, Building material, Machine learning

1. INTRODUCTION

In the past decade, automatic building material recognition (a term used interchangeably with classification in the computer vision community) based on the state-of-the-art information technologies has been a promising research direction in the architecture, engineering, and construction (AEC) industry. Automatic material recognition can improve the efficiency of a variety of tasks, including damage detection and onsite material management and tracking [1,2]. Moreover, it has been an important task to generate as-is building information models (BIMs) that reflect the as-is conditions of facilities, which can be applied for various applications such as construction progress management, operation and maintenance (O&M) of existing buildings, and building performance analysis [3,4]. An as-is BIM, which can be applied for various applications such as construction progress management, operation and maintenance (O&M) of existing buildings, and building performance analysis [3,4], contains not only the geometric information of a building but also non-geometric information of building elements including building materials [5]. The material information is essential for many BIM applications such as building energy simulation and facility maintenance and repair. Therefore, there is a high demand for automatic building material recognition in order to generate semantically rich as-is BIMs containing material information.

Applying machine learning techniques for automatic building material recognition has been a popular approach over the past years. Currently, the proposed material recognition methods are mainly based on 2D images. The core technique of image-based methods focuses on using the visual features of building

materials such as colour, texture, roughness, and projection [3,6,7] for automatic recognition. However, image-based methods are heavily influenced by illumination conditions. Different illumination conditions strongly affect the visual characteristics of materials, causing difficulty for image-based building material recognition. Moreover, poor textures on objects and unknown viewpoints also negatively affect the robustness and accuracy of image-based material recognition [7].

Considering the potential of terrestrial laser scanning (TLS) for automatic building material recognition, this research aims to develop an automatic building material recognition approach based on TLS. A TLS with a built-in camera can capture not only the visual features but also intrinsic properties of building materials such as the material reflectance. Meanwhile, unlike passive imaging which is critically dependent on environmental lighting conditions, TLS uses an active measurement technique with infrared lights, which is not affected by environmental illumination conditions [8]. Therefore, TLS has great potentials to achieve more accurate material recognition considering the more types of information provided and higher robustness to changeable lighting conditions.

Moreover, TLS has been extensively adopted for as-is BIMs reconstruction due to its high measurement accuracy and speed [5]. As a result, using laser scan data for building material recognition does not require extra data collection if laser scan data are already collected for as-is BIMs reconstruction. Despite the advantages of TLS, few previous studies have adopted TLS for building material recognition.

2. RELATED WORKS

Image-based material recognition using computer vision techniques has been the dominant non-destructive material recognition method. Brilakis et al. [9,10] are among the first to introduce image-based material classification techniques into the construction industry, and their ground-breaking work validated the feasibility of image-based recognition of construction materials. After that, different image-based methods were increasingly developed for highly accurate, robust, and time-efficient material recognition for better construction management [3,6,7,11,12].

On the other hand, a few studies have explored building material classification based on TLS. The reflected intensity values collected by TLS are first adopted for material classification. For instance, Franceschi et al. [13] indicated that the intensity values from TLS could provide a reliable method to classify the rocks in outcrop conditions based on a series of experiments. Armesto González et al. [14] showed the potential of using the reflected intensity from TLS for the recognition and characterization of certain damages in building materials of historical buildings by combining digital image processing techniques and unsupervised classification algorithms. Riveiro et al. [15] presented a novel segmentation algorithm for automatic segmentation of masonry blocks from 3D laser scan data based on the reflected intensity values.

In addition to the reflected intensity values, some studies have utilized the colour information captured by the built-in camera of TLS for material classification. For example, Hassan et al. [16] confirmed the availability of material identification using the reflected intensity and Red-Green-Blue (RGB) values from TLS by a series of experiments. The experiment results showed that the scanned materials had different reflected intensity distributions, and the recorded RGB colour values could be used as a secondary parameter for material identification. Valero et al. [17] achieved automatic segmentation of individual masonry units and mortar regions in digitized rubble stone constructions based on coloured laser scan data acquired by TLS. The scan data of the target surface was converted into 2D depth maps as a feature for automatic segmentation, and colour information was used as another feature. The experimental results demonstrated the effectiveness of the technique.

Although image-based material recognition methods have made great advancement and are more extensively adopted than TLS-based methods, their applications in the real-world environment still face challenges due to the complex field conditions and their dependence on environmental illumination conditions. The ability to capture more types of information and the use of active measurement technique makes TLS-based material recognition more promising.

However, the previous studies on TLS-based material recognition are either based on only laboratory experiments in a controlled environment [13,14,16] or for the recognition of only one or two categories of building materials [15,17]. To tackle the limitations of previous studies, this study examines the feasibility of using TLS data for the recognition of ten different common building materials in real-world environments.

3. DETERMINATION AND CALCULATION OF FEATURES

In this study, the features used for automatic building material recognition are 1) material reflectance, 2) colour, and 3) surface roughness. For each scan point, the TLS collects a set of attributes comprising of the reflected laser beam intensity, RGB colour values, and x-y-z coordinates. The values of the chosen features can be calculated based on the collected information. The reasons for the determination of features and the calculation process of each feature are explained in the following subsections.

3.1. Material reflectance

For each scan point, the TLS provides a reflected laser intensity value (I_r), which is determined by the type of material and scanning parameters. Although I_r is recommended to be a feature for material classification in previous studies, different materials are likely to present similar I_r values because various scanning parameters can also affect I_r . Instead, among all the factors that affect I_r , the material reflectance ρ is the only intrinsic property of a certain material. In other words, the same material always has the same ρ value even though other factors are varying. Therefore, the material reflectance ρ is adopted as a feature for material recognition in this paper.

For calculating the ρ value from the TLS data, previous studies have proposed some methods [13,18], but these methods are not practical enough in the real-world environment because they require to place the same reference target in different scanning scenes to be a reference for the ρ calculation of the scanning target.

This study developed a reference target-free method for calculating the ρ values of different materials. Considering the realistic scanning scenes of buildings mostly being near-distance scanning, this study assumes that the scanning range R from the TLS to the scanned target is less than 10 m. For each laser scan point, the ρ value can be calculated for material recognition in the following three steps. First, the neighbouring points of a scan point are obtained by finding all points within a $s_1 \times s_1$ square that is centred at this scan point. As shown in Figure 1, all the points within the blue square become the neighbouring points of the blue point P_i . Second, the $\cos\theta/R^2$ values of the all neighbouring points are calculated by Equation (1) which is derived in the condition of long-distance scanning in previous studies [19-24]. Meanwhile, the I_r values of the neighbouring points are extracted from the laser scan data. Third, a linear function is fitted into the $\cos\theta/R^2$ and I_r values of neighbouring points according to Equation (2). This Equation is obtained based on a series of field tests using FARO Focus^{S70} laser scanner in this study, and the coefficient ρK_1 , ρK_2 or ρK_3 is obtained. Because ρK_1 , ρK_2 or ρK_3 is fixed when using the same TLS and it is difficult to estimate their specific values, ρK_1 , ρK_2 or ρK_3 is used in this study to represent ρ as the material reflectance for material recognition.

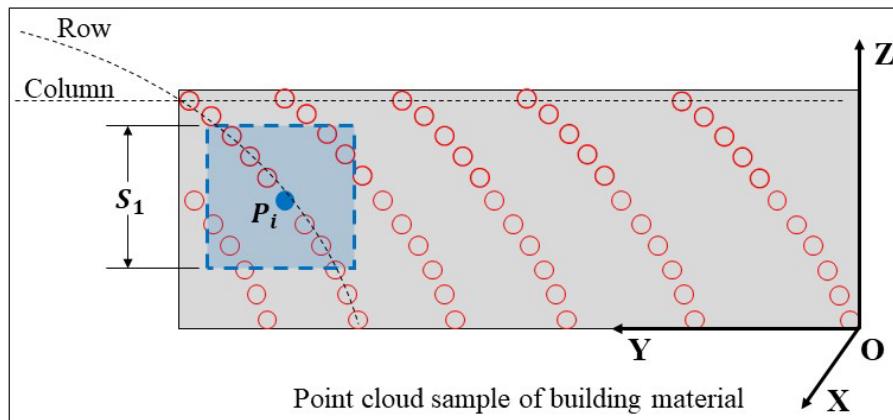


Figure 1. Calculation of ρ based on neighbouring points of a scan point

$$I_r = \rho K \frac{\cos\theta}{R^2} = \rho K \sqrt{\frac{x^2 + y^2}{x^2 + y^2 + z^2}} \quad (1)$$

where K is a total coefficient which comprises the transmitted intensity, the receiver aperture diameter, the atmospheric transmission factor, and the system transmission factor, and the K will be a fixed value

when using the same TLS for scanning. θ is the laser beam incident angle on I_r . x, y, z are the Cartesian coordinate values of each scanned point.

$$\left. \begin{array}{l} I_r = \rho K_1 \frac{\cos\theta}{R^2} + b_1, \quad 4 \text{ m} < R < 10 \text{ m} \\ I_r = \rho K_2 \frac{\cos\theta}{R^2} + b_2, \quad 2 \text{ m} < R < 4 \text{ m} \\ I_r = \rho K_3 \frac{\cos\theta}{R^2} + b_3, \quad R < 2 \text{ m} \end{array} \right\} \quad (2)$$

where b_1 , b_2 , and b_3 are three different constant terms. They exist because of the equipped brightness reducer in the scanner to protect the scanner from extremely high received laser intensity [24,25].

3.2. Colour

A TLS with a built-in camera can capture the colour information of each scan point and record as RGB colour space (RGB values from 0 to 255). The RGB values can potentially help in building material recognition. Object colours have been extensively used for not only object and material recognition using 2D images in the computer vision community [3-5,26], but also material classification using laser scan data [16,17]. According to the literature, the Hue-Saturation-Value (HSV) colour space is preferred than the RGB colour space because of its better robustness under variable illumination conditions. Therefore, this study also adopts the HSV colour space as the features for automatic building material recognition. The translation function from RGB to HSV is described in [27], as follows:

$$r = \frac{R}{255}, g = \frac{G}{255}, b = \frac{B}{255}$$

$$Ma = \max(r, g, b), Mi = \min(r, g, b), \Delta = Ma - Mi$$

$$H = \left\{ \begin{array}{ll} 0^\circ, & \text{if } Ma = Mi \\ 60^\circ \times \frac{g - b}{\Delta} + 0^\circ, & \text{if } Ma = r \text{ and } g \gg b \\ 60^\circ \times \frac{g - b}{\Delta} + 360^\circ, & \text{if } Ma = r \text{ and } g < b \\ 60^\circ \times \frac{b - r}{\Delta} + 120^\circ, & \text{if } Ma = g \\ 60^\circ \times \frac{r - g}{\Delta} + 240^\circ, & \text{if } Ma = b \end{array} \right. \quad (3)$$

$$S = \left\{ \begin{array}{ll} 0, & \text{if } Ma = 0 \\ \frac{\Delta}{Ma}, & \text{otherwise} \end{array} \right. \quad V = Ma$$

3.3. Surface roughness

With the millimetre-level laser beam diameter, TLS can capture microscopic characteristics of building materials, e.g. surface roughness (R_a). The feasibility of estimating surface roughness based on laser scan data has been proven by previous research efforts [28,29]. In general, each category of building material presents different surface roughness. Previous studies show that it is potential to utilize surface roughness estimated from laser scan data for material recognition. Therefore, this research also uses surface roughness as a feature for automatic building material recognition.

In this study, the surface roughness R_a of a scan point is calculated in the following four steps. First, for each scan point P_i , its neighbouring points are obtained as the points within the $s_2 \times s_2$ square that is centred at this point, as shown in Figure 2. Second, a plane is fitted into the neighbouring points using the M-estimator SAmple Consensus (MSAC) algorithm. The fitted plane M can be expressed as $Ax + By + Cz + D = 0$. Third, the orthogonal distance d_i from each neighbouring point (x_i, y_i, z_i) to the fitted plane is calculated using Equation (4):

$$d_i = \frac{|Ax_i + By_i + Cz_i + D|}{\sqrt{A^2 + B^2 + C^2}} \quad (4)$$

Lastly, the surface roughness R_a at point P_i is calculated as the average d_i value for all the n neighbouring points:

$$R_a = \frac{1}{n} \sum_{i=1}^n d_i \quad (5)$$

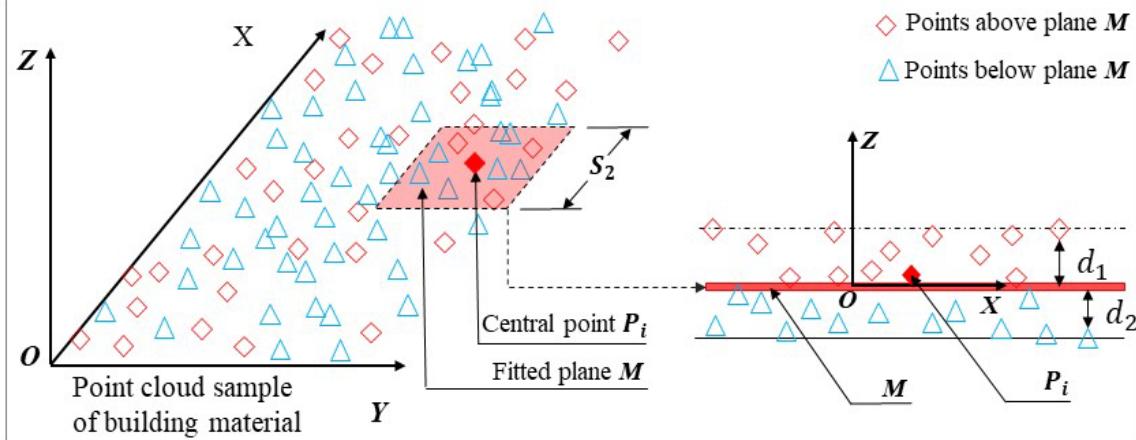


Figure 2. Calculation of surface roughness based on neighbouring points and fitted plane

4. EXPERIMENTS

Taking the existing construction material libraries as a reference, we created a common building material set. This study considered ten different categories of materials, including concrete, mortar, stone, metal, painting, wood, plaster, plastic, pottery, and ceramic. Although being extensively used in buildings, glass is not chosen in this study because TLS has difficulty in capturing transparent objects. For the ten categories of materials, one specific commonly-used building material was selected from each category.

A FARO Focus^{S70} TLS was used to collect laser scan data of the ten materials. This TLS had a measurement range of 0.6 to 70 m, and a field of view of 300° vertically and 360° horizontally. The beam diameter was 2.12 mm, and the divergence was 0.3 mrad [30]. The laser scan data of the ten building materials were collected from buildings in the National University of Singapore. The collected scan data included both building interiors (i.e. ceilings, walls, and floors) and exterior facades. The data processing was executed in MATLAB2019a [31] after the laser scan data were extracted from the TLS's software FARO SCENE [32].

We created a dataset with $2 m < R < 4m$ contained 41,000 data points (approximately 4,100 data points for each building material), and the dataset with $4 m < R < 10 m$ contained 53,000 data points (approximately 5,300 data points for each building material). This study did not choose $R < 2 m$ because the scanning scenes with it are very rare in laser scanning of buildings. Each data point comprised a building material category label, ρ value, H, S, and V values in the HSV colour space, and R_a value. To find the best combination of features, this study tested different combinations of features (ρ , HSV values, and R_a). Besides, the I_r value and RGB values were also considered in the comparisons. To identify the best recognition model, different supervised learning classifiers were explored.

Recognition accuracy was used in this research to measure the performance of different recognition models. The accuracy of a recognition model can be quantified by Equation (6).

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN} \quad (6)$$

where TP , TN , FP , and FN are the numbers of True Positives, True Negatives, False Positives, and False Negatives, respectively.

4.1. Experiment Results

We trained different classifiers with different feature combinations in Classification Learner of MATLAB2019a. Two accuracy performance matrixes with different ranges of R are obtained, as shown in Tables 1 and 2.

Table 1. The accuracy performance matrix of building material recognition when $2 m < R < 4 m$

	DTs (%)	Das (%)	NBs (%)	SVMs (%)	KNNs (%)	Ensembles (%)
ρ	61.0	54.7	59.0	60.3	<u>61.8</u>	58.6
R_a	28.0	26.5	28.8	30.1	28.1	<u>31.4</u>
HSV	85.7	73.4	78.5	82.7	88.1	<u>88.6</u>
RGB	71.9	78.1	53.5	80.6	87.5	<u>88.6</u>
I_r	<u>40.3</u>	38.8	40.4	38.9	35.4	40.2
$\rho + R_a$	69.3	53.8	65.9	63.8	<u>72.7</u>	70.4
$\rho + HSV$	89.0	86.2	89.1	88.1	94.2	<u>95.0</u>
$R_a + HSV$	86.2	73.5	82.5	89.1	90.0	<u>92.5</u>
$\rho + R_a + HSV$	91.0	88.7	91.2	93.1	95.2	<u>96.1</u>

Table 2. The accuracy performance matrix of building material recognition when $4 m < R < 10 m$

	DTs (%)	Das (%)	NBs (%)	SVMs (%)	KNNs (%)	Ensembles (%)
ρ	77.0	67.6	74.9	72.0	<u>77.5</u>	75.7
R_a	<u>30.9</u>	26.6	26.0	26.0	24.7	29.5
HSV	71.5	67.1	71.9	72.2	75.0	<u>77.7</u>
RGB	65.8	68.2	48.8	60.8	75.0	<u>76.3</u>
I_r	<u>29.7</u>	24.6	24.6	24.5	28.5	29.4
$\rho + R_a$	85.3	71.5	78.6	79.1	<u>87.2</u>	86.8
$\rho + HSV$	93.5	88.9	91.2	90.8	95.6	<u>95.9</u>
$R_a + HSV$	77.9	69.5	77.0	80.0	82.7	<u>84.4</u>
$\rho + R_a + HSV$	94.1	89.6	95.2	90.5	96.6	<u>97.0</u>

According to Table 1, when $2 m < R < 4 m$, using ρ , HSV , and R_a as features and Ensemble as the classifier produced the highest recognition accuracy of 96.1%. According to Table 2, when $4 m < R < 10 m$, using ρ , HSV , and R_a as features and Ensemble as the classifier produced the highest recognition accuracy of 97.0%. In conclusion, using ρ , HSV , and R_a as features and Ensemble as the classifier always had the highest recognition accuracy, showing an average recognition accuracy of 96.5% when $2 m < R < 10 m$.

As mentioned above, this study used ρ instead of I_r , and HSV instead of RGB as the features for material recognition. The experiments also tested the recognition accuracy when using ρ , I_r , HSV , or RGB as the only feature. According to Tables 1-2, using ρ as the only feature had accuracies of 61.8%

and 77.5%, respectively, which were higher than the accuracies of 40.4% and 29.7% when using I_r . The experimental results showed that ρ was a much better feature for material recognition than I_r . For the comparisons between HSV and RGB, using HSV colours as the only features had accuracies of 88.6% and 77.7%, respectively. The accuracies became 88.6% and 76.3% when using RGB colours. Although the accuracies were very similar, HSV colours still had a better overall performance than RGB colours. The comparisons proved that selecting ρ and HSV colours as features was preferred.

We further compared the performances when using any two of ρ , HSV , and R_a as the features (i.e. $\rho + R_a$, $\rho + HSV$, and $R_a + HSV$). Tables 1-2 proved that using the combination of any two features performed better than using any single feature on recognition accuracy. The results indicated that all the features were useful for improving recognition accuracy.

Regarding the comparisons of classifiers, the experimental results showed that the ensemble algorithm was the best classifier. The result is consistent with the conclusion introduced in a previous study [26]. According to the experimental results, the algorithm with the highest recognition accuracy was the bootstrap-aggregated decision trees (Bagged Trees) in both Tables 1 and 2.

4.2. Discussion

To further understand the material recognition results, we used the confusion matrix to analyse the recognition performance for the case with the highest recognition accuracy (i.e. using $\rho + R_a + HSV$ as features and Bagged Trees algorithm as the classifier). The recognition results for both $2 \text{ m} < R < 4 \text{ m}$ and $4 \text{ m} < R < 10 \text{ m}$ were combined, and the confusion matrix is shown in Figure 3. Each row of the confusion matrix shows the percentage of TP and FN for a true material class. It is found that all ten categories of materials produced a recognition accuracy of at least 92%. The painting material showed the highest TP percentage of 100%, indicating that all the data of the painting material were correctly recognized. The mortar material presented the lowest recognition accuracy of 92%. It is shown that 7% of mortar data were wrongly recognized as stone. This phenomenon indicated that the features of stone material were similar to these of mortar material.

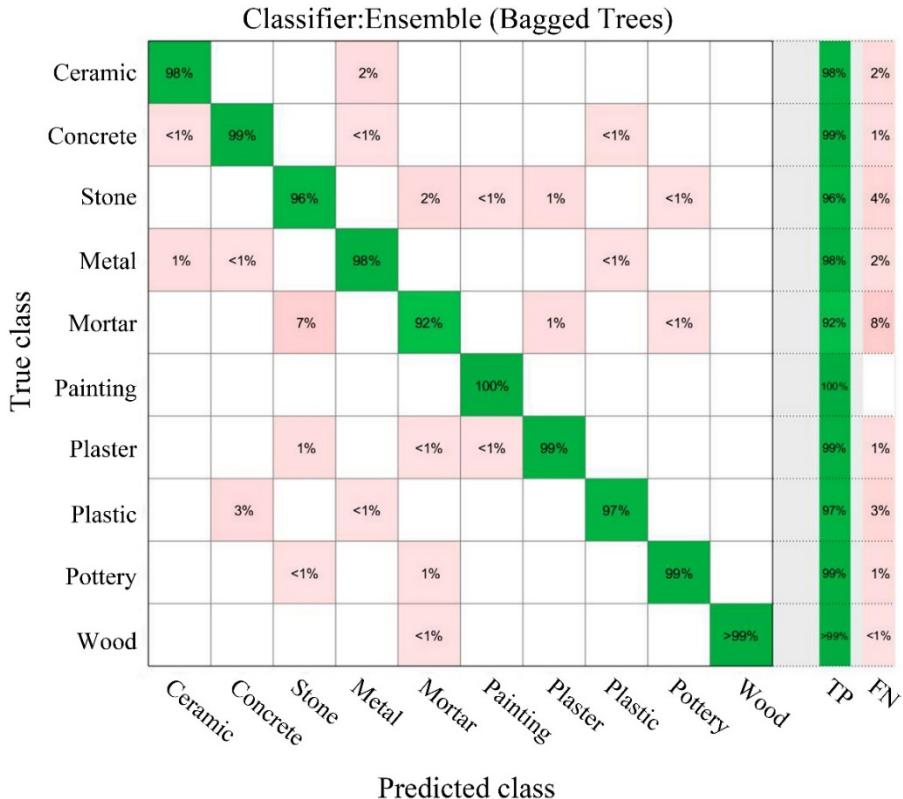


Figure 3. Confusion matrix of the case with the highest recognition accuracy (i.e. using $\rho + R_a + HSV$ as features and Bagged Trees algorithm as the classifier)

5. CONCLUSION

Automatic material recognition can improve the efficiency of a variety of tasks, including damage detection and onsite material management and tracking. Particularly, as BIM is popularly adopted in the

AEC industry, there is a high demand for automatic building material recognition in order to generate semantically rich as-is BIMs containing material information. While the previous studies are focused on material recognition methods based on 2D images, this study proposes to combine machine learning techniques into TLS for material recognition because TLS provides more types of information and has better robustness to lighting conditions.

In the proposed method, material reflectance ρ , HSV colours, and surface roughness R_a are used as recognition features. The ρ value is an intrinsic property of a certain material, and it can be inferred from the TLS data. The HSV colours are used in this study instead of the RGB colours because the HSV colours show better robustness to varying lighting conditions. The HSV colours are calculated from RGB colours that are obtained from the raw laser scan data. The R_a value is calculated as the average distance from the neighbouring points of a scan point to the fitted plane of the neighbouring points.

To validate the proposed method, we used different supervised learning classifiers to test the different combinations of features. Ten different categories of materials, including concrete, mortar, stone, metal, painting, wood, plaster, plastic, pottery, and ceramic, are selected as test samples. A FARO Focus^S70 TLS was used to collect laser scan data of the ten different materials. The laser scan data were processed in MATLAB2019a to calculate the above-mentioned features. In the model training and testing, we used 80% of the entire dataset to train the recognition model and the rest 20% to test the trained model. The experimental results showed that using ρ , HSV, and R_a as features and Ensemble as the classifier realized an average recognition accuracy of 96.5%. Experimental results also validated that ρ was a much better feature for material recognition than I_r , and HSV colour outperformed RGB colour. Further analyses showed that all the ten categories of materials produced a recognition accuracy of at least 92% when using $\rho + R_a + HSV$ as features and Bagged Trees algorithm as the classifier.

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Review of Construction Business Intelligence Research

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Abstract: With the 4th industrial revolution, many advanced information technologies are being applied to the area of construction engineering and project management. These applications are usually focusing on design, construction and operation stage and are producing many meaningful fruits. Even though these studies are very important for the development of the construction industry, this study insists that the other stage perspective such as construction business also should be emphasized. Because business phase has significant impacts on the success of a construction project as well as design, construction and operation phase. So, this study reviewed the intelligent-approach papers in planning and marketing, estimation and bid, contract and claim, and project financing fields. This study provides some insights such as values, difficulties, limitations and future directions of business intelligence application.

Key words: Construction business, Intelligent construction, Data science, Information technology

1. INTRODUCTION

The beginning of the fourth industrial revolution was declared by Klaus Schwab at the World Economic Forum in 2016. It has become a global trend and terms like ‘big data’, ‘artificial intelligence’, ‘machine learning’ have overflowed all around the world. With the exponential growth of data availability and computing power, data-driven analytics have become possible to produce meaningful insight and to be applied for solving real-life problems [1]. Along with the increased research attention on the fourth industrial revolution techniques, governments have established national-level action plans to support the innovative growth of industries as well as private companies have made massive investments on related projects [2]. The construction industry also has been responding to the fourth industrial revolution by technology transformation from analog to digital along the value chain of construction projects. Boston Consulting Group (BCG) categorized digital technologies in construction industry into four groups as the user interfaces and applications, software platform and control, digital-physical integration layer, and sensors and equipment [3]. However, applications of these technologies usually have been focused on design, construction and operation stage. Even though these studies are very important for the development of the construction industry and are producing many meaningful fruits, the other stage perspective such as construction business also should be emphasized more. This business phase has significant impacts on the success of a construction project as well as design, construction and operation phase [4]. Therefore, this study aims to review construction business intelligence research in early stage of construction project as planning and marketing, estimation and bid, contract and claim and project financing to suggest directions towards effective business intelligence application in the construction domain.

2. LITERATURE REVIEW

This study reviewed academic papers related to business intelligence in early stage of construction project using the state-of-the-art techniques as shown in Table 1. Abbreviations frequently used in this study are at the end of the paper.

Table 1. Summary of reviewed papers in the construction domain

Field	Topic	Methodology	Data source	Reference
Planning & Marketing	Cost index estimation	LS-SVM, DE	Open data	[5]
	Project portfolio management	NLP	Interview	[6]
	Bid/no-bid	SVM	Survey	[7]
	Big data collection	WC, TM	WWW	[8]
	Go/no-go decision	NN	-	[9]
Estimation & Bid	Cost performance prediction	SVR	Survey	[10]
	Cost estimation	GRNN	Private	[11]
	Cost estimation	ANN	World bank	[12]
	Profitability prediction	SVM	Open data	[13]
	Cost estimation	GRNN, MLF	Public	[14]
	Cost estimation	MLP	Survey	[15]
	Cost estimation	MLP, RBF	Public	[16]
	Duration estimation	MLP	Public, Survey	[17]
	System framework	Big data	-	[18]
	Bid competitiveness	GA, ANN	Public	[19]
	Bid mark-up size	ANN	Survey	[20]
	Risk assessment	TM, SVM	Public	[21]
	Risk assessment	TM	Private	[22]
	Contractor default prediction	ESVM	Open data	[23]
	Financial distress prediction	SFNN	Open data	[24]
Contract & Claim	Financial distress prediction	SVM, ANN, NB, KNN	Open data	[25]
	Business failure prediction	Big data, ANN	Open data	[26]
	Collusion detection	ANN	Public, Journal	[27]
	Litigation outcome prediction	SVM, NB, NN	Public	[28]
	Legal knowledge extraction	TM, SVM, NB,	Public	[29]
Project Financing	Escalation claim outcome prediction	MLP, GFF	-	[30]
	Claim outcome prediction	MLP, GFF	-	[31]
	Poisonous clauses extraction	TM	Private	[32]
	Contract analytics and monitoring	TM	Private	[33]
	Financial optimization for PPP project	GA	-	[34]
Risk analysis in PPP project	ANN, MCS	-	[35]	
	GALP	-	[36]	

2.1. Planning and Marketing

In the present study, planning and marketing phase of construction project refer to market prediction, country selection, go/no-go decision and early screening of bad project. Cheng et al. suggested a hybrid intelligence approach for construction cost index estimation of Taiwan construction market [5]. They

used 17 cost index influencing factors related to economic, financial, stock market and energy which can be acquired from open data source. In this study, the hybrid of LS-SVM and DE showed better performance than other machine learning techniques such as evolutionary support vector machine inference and backpropagation neural network. Costantino et al. developed a project selection model in view of project portfolio management using ANN [6]. They assessed critical success factors of 150 Italian projects cases by expert interview. Then they employed MLP to classify project success or failure. Sonmez and Sozgen developed a bid decision-making model for offshore oil and gas platform fabrication projects based on the SVM method [7]. They used a five-point scale to assess eight variables which have impact on bid/no bid decision. In this study, SVM method outperformed NN and conventional regression method. Moon et al. developed a document management system in order for information acquisition of international construction [8]. They proposed automatic data collection method using the WC technique from Korean construction-related websites. Then they employed NLP and TM techniques to develop the document management system which provides information of target country in the form of search engine using tagged keywords. Utama et al. suggested a go/no-go decision support model for international construction project based on a hybrid of NN and fuzzy theory [9]. They applied learning process of NN in tuning the membership function used in the fuzzy theory. The suggested model was developed based on the simulated cases of Indonesian contractors.

Many researchers have studied the marketing field in the international construction domain; mainly topics related to market selection [37-43] and entry strategy [44-49]. Nevertheless, most previous studies related to marketing are limited in employing intelligent approaches such as big data and AI. In contrast to the construction sector, marketing field of other business sector are undergoing dramatical paradigm shift with a large amount of consumers' information as big data and advanced data science tools and techniques [50]. Development of digital technologies changed business ecosystem, which targets unspecified individuals, from offline to online and from analog to digital [51]. Against this backdrop, the social media analytics and intelligence research have been developed, which aims to extract insight and inherent information from consumer's data using the WC, opinion mining, content analysis, network analysis, topic extraction [52]. For example, Samsung Electronics analyze social media to investigate what characteristics its consumers have and what are current issues related to its products, and it changes marketing strategies in real time to satisfy consumers' needs [53].

2.2. Estimation and Bid

This study reviewed papers related to project performance prediction, bid competitiveness analysis, risk analysis based on bid-related documents, prediction of financial crisis of contractor and collusion detection during tender process. Project performance prediction is not a new subject. A number of research papers have continuously suggested performance prediction model, mainly cost estimation, with limited available information based on statistic approach or case study. With the development of data science techniques, recently published papers have attempted to improve the estimation capability of previously suggested models by applying advanced methodologies and algorithms such as artificial intelligence. Son et al. suggested a cost performance prediction model that can be applied in the planning stage based on the SVR with PCA [10]. The scope of this study was limited to commercial building projects and they used 84 building projects executed in Korea. They performed a questionnaire survey, which consists of project information including cost overrun ratio and 64 variables of project definition ration index for building projects introduced by the Construction Industry Institute (CII). Yip et al. predicted the maintenance cost of construction equipment based on the GRNN model and compared it with conventional Box-Jenkins time series model [11]. Data for the maintenance cost of construction equipment were collected from a contractor across to different operational divisions respectively. This study concluded that although traditional time series approaches can analyze overall trend and fluctuation patterns, and historical changes over time, non-linear neural network model showed better performance in multivariate modeling because of reflecting dynamic relations between object-related variables. Cirilovic et al. targeted road rehabilitation and reconstruction projects in Europe and Central Asia for cost estimation using projects data from the World Bank study [12]. They compared ANN and MRA approaches, and ANN model outperformed MRA model. Zhang et al. developed a prediction model for forecasting profitability of 489 Chinese construction companies listed on China's A-shares using the PCA and SVM [13]. They used six profitability indicators; return on assets, return on equity, return on capital, earnings per share, profit margin from main business, and return on sales. In addition, this study compared the SVM model with the NN model. They argued that the SVM model showed better performance at predicting profitability than the NN model when analyzing with small samples.

Dursun and Stoy developed a conceptual cost estimation model in pre-planning phases based on the multistep ahead approach using LR, GRNN and MLF methods with 657 building project cases from Germany [14]. The data was collected from the cost information center of the German Chamber of Architects. This study used predicted values of building-element quantities as additional step compared to the conventional single-step ahead approach, and they concluded that quality and quantity of available information has more significant impact on cost estimation than which methodology is used. Marzouk and Elkadi focused on estimating water treatment plants costs executed in Egypt based on the factor analysis and MLP [15]. They identified 33 cost variables through literatures and expert interviews, and collected 160 questionnaires which assessed the impact of the variables. They developed eight NN models combining training types (batch / online / mini batch), optimization algorithm (scaled conjugate gradient / gradient descent), and number of hidden layers (one / two). As a result, a model that consists of one hidden layer using batch training type and gradient descent optimization algorithm showed the lowest MAPE. Bayram et al. compared conventional cost estimation method used in Turkey with MLP and RBF methods and they identified the radial basis function method was superior with the lowest variance with actual values [16]. Nani et al. applied MLP method to estimate duration of bridge construction projects in Ghana [17]. They collected 30 historical data and 100 questionnaires related to bill of quantity from government institution of Ghana. Unexpectedly, the performance of regression and ANN model were not so different in this study.

For bid competitiveness analysis from contractor's perspective, Zhang et al. introduced a system framework that evaluates tender price of construction project using big data [18]. This study focused on big data collection rather than detailed methodologies at the data science perspective. They suggested three types of cost data collection sources; accumulated research cases of the team on practical projects, agreement signed with companies, and agreement with the government construction project management departments. Chou et al. suggested a project award price prediction model using hybrid AI techniques [19]. Based on the GA basically, non-linear regression and ANNs were combined, and they presented 13 prediction models using various parameter values. They collected bid invitation documents and bid award data from government procurement system and Taiwan public construction commission. The result of this study revealed that ANN based models show higher performance than conventional methods for realistic simulations. Polat et al. compared performance of ANN and MRA techniques in estimating bid mark-up size of public construction projects [20]. They used questionnaire survey and collected 80 cases from 27 Turkish contractors. As a result, there was only slight difference in model performance between ANN and MRA models. From the risk analysis perspective, Lee and Yi studied on risk assessment in bidding phase [21]. They developed a project uncertainty prediction model in the bidding process based on integration of unstructured text data and structured numerical data. They collected bidding information of public infrastructure projects ordered by the California Department of Transportation. This study applied the TM technique for extracting risk-related terms from bidding documents in order to improve the accuracy of the risk prediction model which used only the numerical data. In this study, the SVM outperformed other classification models such as ANN, KNN, and NB. Son and Lee developed schedule delay risk estimation model for offshore oil and gas EPC projects using TM technique [22]. They used the scope of work in contract and lessons learned documents written by a private contractor for 13 actual cases. After determining critical terms which have significant impact on schedule delay, they extracted the critical terms through the NLP and developed a regression model to estimate schedule delay considering risk.

There are researches performed in view of the owner and investor's perspective, mainly focusing on the contractor's financial distress prediction. Tseng et al. introduced a prediction model for default of construction contractors in the United States of America (USA) using the ESVM [23]. Target companies for analysis were total of 1,422 construction contractors listed on the New York Stock Exchange, American Exchange, and Nasdaq. Financial data were collected from the Compustat Industrial database and the Center for Research in Securities Prices (CRSP), and a total of 20 input variables were used, which are categorized as liquidity, leverage, activity, and profitability. They employed the ESVM because defaulted events show extreme distribution characteristics, which produce sample selection biases during the learning process. Chen proposed a hybrid model combining three algorithms of self-organizing feature map optimization (SOMO), fuzzy logic control (FLC), and hyper-rectangular composite neural network (HRCNN) to predict financial failure of construction companies in Taiwan [24]. They used 1,615 datasets for data analysis, which consist of quarterly financial reports of 42 companies for 11 years. Choi et al. developed a prediction model for financial distress of contractors in Korean construction industry using ensemble learning [25]. They collected financial status data of

contractors such as financial statements and credit ratings from Korean credit rating agencies. Then, this study developed an ensemble classifier using the six classifiers, namely, SVM, NB, ANN, C4.5, LR and KNN. Alaka et al. suggested failure prediction framework of construction firms in UK based on big data analytics and ANN. In this study, they relatively focused on framework architecture for handling large amount of data with short computing time than data analysis [26]. The topic predicting latent corporates which are exposed to financial crisis has been studied widely in other sectors too, especially in the banking sector [54]. Furthermore, Anysz et al. suggested collusion detection model during tender procedures using ANN classifier [27]. They used 249 tender records of public projects collected from Poland Public Procurement Bulletin and European journal TED (Tenders Electronic Daily). The object of this model is to classify public tender procedures as ‘Free from collusion’, ‘Collusion suspected’, and ‘Collusion highly expected’.

2.3. Contract and Claim

In the light of business management in early stage of construction project, contract and legal documents analysis have been studied. Especially, with the development of NLP and TM techniques, studies based on unstructured text data have been presented recently. Mahfouz and Kandil developed a litigation outcome prediction model using three ML techniques, namely SVM, NB and NN classifiers [28]. They gathered 400 construction precedent cases from the federal court of New York through a web database. They identified 15 significant factors affecting litigation outcome as input attributes of ML models. In this study, the SVM based model outperformed other ML models with 98% of accuracy. In addition, Mahfouz et al. suggested another ML based classifiers using textual unstructured data that determines whether judgement of court would favor to owner or contractor from construction contract [29]. They collected a total of 600 actual legal cases through the same approach used in [28]. For the classifier, they developed legal factor extraction model from textual document using TM techniques for handling unstructured data and the Term-Frequency mechanisms for weighting word tokens. In this study, the NB model had better performance than SVM, decision tree and projective adaptive resonance theory. Chaphalkar and Sandbhor suggested outcome of escalation claims prediction model using NN approach [30]. They used 419 claims arisen in the Indian construction industry. They studied 10 major factors influencing the arbitral decision making for outcome of claim, then the factors were converted into binary format as input attributes of NN models according to whether the factor exist in contract or not. Furthermore, Chaphalkar et al. extended the previous study of [30] to various types of claims [31]. Based on 831 cases resolved by arbitration in the Indian construction industry, they identified 16 intrinsic factors caused claim and used the factors as input attributes of NN model. They developed two NN based models employing MLP and GFF. Lee et al. introduced a rule-based NLP model that automatically extract poisonous clauses from a contract of international construction project [32]. They developed preprocessing rules, syntactic rules, and semantic rules to identify risk-related clauses based on the International Federation of Consulting Engineers (FIDIC) standard contract conditions. Marzouk and Enaba proposed contract analytics and monitoring model based on TM [33]. The suggested model extracts important terms from contract, retrieve similar cases and correspondence of employer and visualize previously extracted contract-related information for managerial purpose. They implemented a case study executed in Egypt in order for the model validation.

2.4. Project Financing

Publication of academic papers related to the public-private partnership (PPP) project has increased constantly and research on economic feasibility and capital structure has been the one of popular topics of PPP studies [55]. Most previous studies investigated economic viability and value for money (VFM) employing option pricing theory mainly, however, not many studies have been searched applying advanced data science techniques. Iyer and Sagheer suggested a financial optimization model for PPP project based on GA method considering not only viability of capital structure but also bid winning potential [34]. Based on 13 project characteristics of BOT road project, the proposed model suggested optimal equity and grant ratio to maximize return on equity and bid-winning probability. Shahrara et al. employed ANN to estimate expected fee for build-operate-transfer (BOT) project during concession periods. Because the purpose of this study is to calculate appropriate fee with respect to surrounding conditions, they created 1,871 scenarios using MCS rather than collecting actual data [35]. Alavipour and Arditì suggested a financing optimization model integrated with time-cost tradeoff analysis based on the GALP, which is an integration of GA and linear programming [36]. This model considered not

only several financing alternatives such as short-term loan, long-term loan, and line of credit but also time-cost tradeoff and the finance-based scheduling problems.

3. DISCUSSION

Conventional statistic approaches are limited to solve real world problems because of assumptions of linearity, normality, independence among variables [56]. To overcome such limitations, data mining and AI techniques have been employed oftentimes recently. Compared with traditional methods, ANNs have advantages in applying practice because not only input data do not have to satisfy various assumptions but also ANNs are more resistant to noise and errors in the data set [12]. In other sectors, many studies employed advanced data science techniques to support establishing business strategies, for example, electricity price forecasting [57; 58], shared bicycle demand prediction [59], natural gas consumption estimation [60], aircraft spare parts demand forecasting [61], agricultural grain commodities prediction [62], medical costs inflation rate forecasting [63], and so on. With respect to recent trend of applying advanced data science techniques, research related to business phase of the construction project also has been widely performed, especially in predicting or estimating project performance. However, business intelligence based on data-driven analysis is difficult in construction domain because of unique characteristic of the construction industry such as uniqueness of product, limited number of customers, order-based market, long lead time from project start to finish, a small amount of accumulated data. In addition, the TM technique, which aims to extract meaningful information such as patters, trends, or relationships from textual unstructured data, has recently received attention along with the development of big data and data science. There is a tremendous amount of textual data on the WWW and many industrial sectors seek to analyze such open data for supporting their business, especially in marketing phase using social media analytics. However, it is limited to collect data from the WWW in construction business because customers of construction project are not unspecified individuals, but relatively small number of clients. In addition, although a large portion of corporate information is in textual data format [64], limited accessibility to sensitive business documents of public and researchers in the construction domain makes difficult to perform research using practical textual data. Data availability is especially important when applying the fourth industrial revolution techniques. Nevertheless, the research in construction sector usually suffer from lack of data [65; 66]. Against these backdrops, the authors of present paper recommend directions towards effective business intelligence application in the construction sector as follow; First, BIM based information management platform for business phase is necessary. BIM is one of the promising information management tools to innovate construction business and improve productivity through embracing digitalization [67]. However, BIM related research and development has mainly focused on project execution phase for integrating design and construction information. Its value chain should be extended to early stage of construction project for business management and supporting decision making [68]. Accumulating and analyzing various data for business phase such as construction market information, clients and competitors information, tender information for new projects and feasibility studies documents would be provide meaningful insight towards better business. Second, industry-academic cooperation should be activated more. Many companies, especially small-medium construction companies, are insufficient in knowledge management. Corporations usually lack manpower and time to invest in data analysis for extracting meaningful insight although they have practical data, whereas academics suffer from lack of practical data for investigation due to confidentiality. Industry-academic cooperation for business intelligence research and development would be win-win strategy for innovation of construction industry and business management in the fourth industrial revolution era.

4. CONCLUSION

This study briefly reviewed academic literature related to construction business intelligence in planning and marketing, estimation and bid, contract and claim and project financing fields over ten years. Although the fourth industrial revolution techniques considerably impact the research of construction domain, it seems one step behind than other sectors because of unique characteristics of construction industry. This study focused on briefly summarizing what purpose existing literature had, which advanced data science technology has been employed, and where the researchers collected data from. Detailed explanation will be presented at the ICCEPM 2020 conference.

ABBREVIATION

AI	Artificial Intelligence
ANN	Artificial Neural Network
BIM	Building Information Modeling
C4.5	Commercial version 4.5
DE	Differential Evolution
ESVM	Enforced Support Vector Machine
GA	Genetic Algorithm
GALP	Genetic Algorithm Linear Programming
GFF	General Feedforward
GRNN	General Regression Neural Network
KNN	K-Nearest Neighbors
LR	Linear Regression
LS-SVM	Least Squares Support Vector Machine
MAPE	Mean Absolute Percent Error
MCS	Monte-Carlo Simulation
MLF	Multilayer Feedforward
MLP	Multilayer Perceptron
MRA	Multiple Regression Analysis
NLP	Natural Language Processing
NN	Neural Network
PCA	Principal Component Analysis
RBF	Radial Basis Function
SVM	Support Vector Machine
SVR	Support Vector Regression
TM	Text Mining
WC	Web Crawling
WWW	World Wide Web

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Development of a Collaboration Recommendation Model between Global Consulting Firms using Link Prediction

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Abstract: Global construction and engineering consulting (E&C) firms are actively seeking entry into overseas markets based on loan projects from multilateral development banks to provide a basis for entry into overseas markets and sustainable growth. Bids on these projects are competitive between global top firms in terms of the technical level and price due to the limited number of projects; thus, developing a successful partnership to complement competence has become an essential element to win bids. In this regard, many studies have analyzed enterprises through characteristic analyses or the derivation of influential factors from the past social networks based on social network analysis (SNA). However, few studies have been conducted to reflect the process of changes to analyze collaborative relationships. Thus, this study aims to identify dynamic changes in past social networks and develop a model that can predict changes in the relationships between E&C firms based on similarities or differences between firms, presenting a methodology to target firms for appropriate collaboration. The analysis results demonstrate that the sensitivity of the developed prediction model was 70.26%, which could accurately predict 163 out of 232 actual cooperative cases.

Key words: international cooperative strategies, World Bank ODA, link-prediction, extreme gradient boosting

1. INTRODUCTION

The construction orders for infrastructure have increased, focusing on rapid urbanization and an increase in official development assistance (ODA) investment in developing countries [1]. Based on these circumstances, global engineering and construction consulting (E&C) firms are actively searching for entry to overseas markets and have participated in multilateral development bank (MDB) ODA projects as a means to enter major overseas markets.

However, because bids on MDB ODA projects are competitive with leading global firms, engaging in a consortium or successful partnership with global and local firms that hold various project execution experience is more advantageous for winning projects [2].

In this regard, several studies have analyzed features of past social networks or firms with a high topology in a social network using social network analysis (SNA) for recommending appropriate business partner candidates. However, few studies have been conducted to reflect the process of changes to analyze collaborative relationships with E&C firms. In addition, previously conducted SNA-focused studies were node-oriented analyses, which were focused only on the topology of the firms, and few studies have analyzed the differences or similarities between firms.

This study aims to develop a predictive model of the collaborative relationship reflecting the dynamic changes of the past network based on the successful bid data of the ODA E&C projects ordered by the World Bank. To this end, a ‘link prediction’ technique was applied that predicts future networks based

on link representing relationships between nodes, rather than focusing on the nodes that represent each firms.

2. RESEARCH BACKGROUND

2.1. Social network analysis

Social network analysis (SNA) is a methodology that analyzes the relationship in social network based on a graph of actors in point (node) and their relationships in line (link). In particular, it has the advantage of being able to visualize potential structural types among actors. In addition, the SNA can determine the main actors in the network by using the centrality indicator, and in this study, four centrality indicators (degree centrality, closeness centrality, betweenness centrality, eigen-vector centrality) were used as variables for machine learning.

As an example of SNA application in construction industry, [3] used SNA to analyze the process of changes in cooperative networks within construction projects. In addition, [2] developed a cooperative relationship strategy by utilizing SNA centrality indicators as machine learning variables. As such, SNA is useful in deriving the topology and role of actors in the network. However, there is a limitation in analyzing changes in organic networks, which has recently led to the emergence of link-prediction techniques to reflect organic changes.

2.2. Link-prediction

Link-prediction predicts links that are newly added or removed in the future network based on the current given network, which is used to analyze dynamic changes in the network. This technique is based on the edge or link that represents a relationship between nodes rather than the network centrality indicator of nodes that is primarily used in SNA. The link-prediction analysis methodology is divided into node-based, topology-based, and learning-based methods. This study utilized the learning-based method and used the network topology presented in Table 1 and the difference between nodes for variables for learning.

As an example of link-prediction, [4] explored key factors in building inter-enterprise partnerships by developing a link-prediction system based on Support Vector Machine (SVM). In addition, [5] used link-prediction to analyze manufacturing-service convergence to predict the emerging technology convergence relationship. As such, link-prediction has an advantage in predicting new relationships to be formed through analysis of past network changes. However, studies that have attempted link-prediction in the existing construction industry have been found to be very rare.

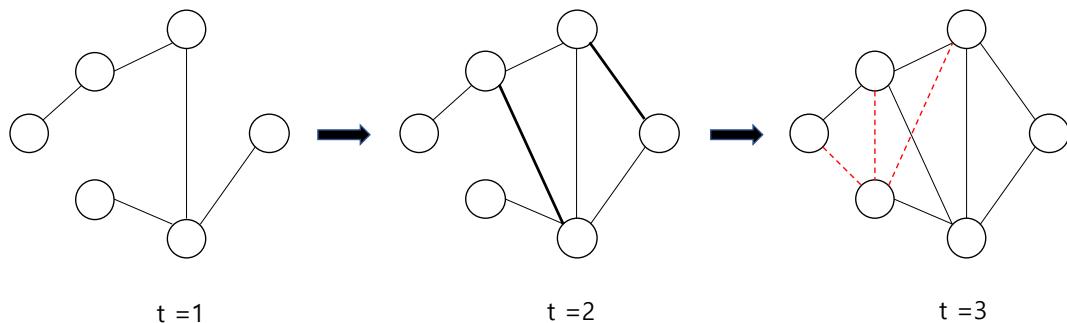


Figure 1. Link-prediction

Table 1. Network topology variables and definitions.

No.	Topology	Abbreviation
1	Preferential Attachment	PA
2	Adamic/Adar	AA

No.	Topology	Abbreviation
3	Resource Allocation	RA
4	Common Neighbors	CN
5	Sorenson Index	SI
6	Salton Cosine Similarity	SC
7	Leicht-Holme Nerman	LHN
8	Hub Promoted	HP
9	Hub Depressed	HD
10	Jaccard's Coefficient	JC

3. LINK-PREDICTION LEARNING MODEL

This study targeted the World Bank's ODA consulting project in three Asian countries (Vietnam, Indonesia and Bangladesh). The data used 'World Bank Finance', an open database provided by the World Bank, and the scope was limited to data that participated in the project with cooperative form because the main purpose of this study was to explore network forming factors. There are 182 cases from 273 companies that participated 471 times in the form of cooperation, and the data were split into three periods based on the number of project participation by country, such as Table 2, in order to establish a learning model that reflects the time flow.

Table 2. Period division based on the number of project participation by country

Country	Year	Period 1	Period 2	Period 3
		2003–2010	2011-2014	2014-2017
Vietnam	Project Participation	77	76	60
	Enterprises	51	46	49
	Year	2003-2005	2006-2011	2012-2017
Indonesia	Project Participation	61	66	59
	Enterprises	41	56	42
	Year	2003-2009	2010-2012	2013-2017
Bangladesh	Project Participation	29	20	23
	Enterprises	19	17	21
	Year	2003-2009	2010-2012	2013-2017

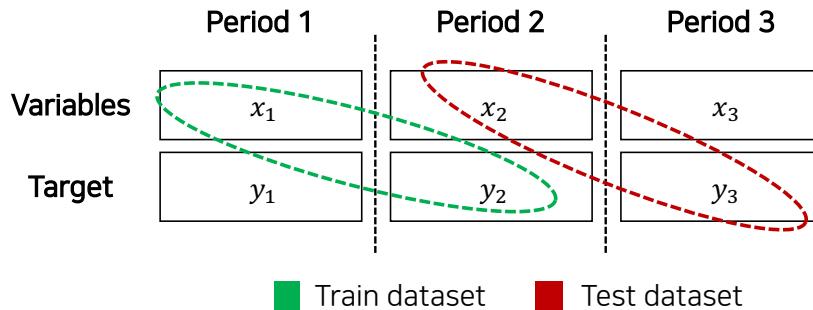
Then, data has been transformed into the link unit, which is the basic unit of the link-prediction learning model. In other words, the link data indicates whether individual nodes (companies) are cooperating (0 and 1) and as a result, it has been converted to 37,128 units, or ${}_{273}C_2$, a combination of 273 companies.

In order to establish a link-prediction learning model, 10 variables based on network topology presented in Table 1 and 10 variables based on data presented in Table 3 were utilized. The data-based variables are based on the differences in network centrality between individual nodes used in the SNA and the differences in information contained in the World Bank database.

Table 3. Data-based variables

	No.	Variables
Difference in information (WB database based)	1	Established year difference
	2	Cooperative form (global-local)
	3	Position difference (leader / member)
	4	ODA experience difference
	5	Enterprise size difference
	6	Average contract size difference
Difference in network centrality (SNA based)	7	Degree centrality difference
	8	Closeness centrality difference
	9	Betweenness centrality difference
	10	Eigen-vector centrality difference

As mentioned in Chapter 1, the learning model in this study was intended to reflect changes over time. Thus, as shown in Fig. 3, the model was trained with the input variables of period 1 and target variables of period 2, and the model was evaluated with the input variables of period 2 and target variables of period 3 respectively. The number of cooperation between training data and test data was 134 and 232 out of 37,128 links, respectively.

**Figure 2.** Data combination for link-prediction model

However, when the number of data to be observed is very small compared to the total number of data, an imbalanced data problem occurs in which the model is learned in the direction of increased accuracy, ignoring the actual examples of cooperation. In this study, a small number of data were interpolated using synthetic minority oversampling technology (SMOTE) [6], and the final established training and evaluation data are as shown in Table 4.

Table 4. Final dataset for link-prediction model

Dataset	Linked	Unlinked	Total
Train	36,994	36,994	73,988
Test	232	36,896	37,128

The final data were used to explore the optimal learning model by utilizing three different machine learning models: random forest, multilayer perceptron, extreme gradient boosting (XGBoost). In particular, in this study, sensitivity was selected as the main model evaluation index to predict actual cooperative cases, unlike the general model evaluation method. As a result, the sensitivity of xgboost model was the highest at 70.26% (correctly predicts 163 out of 232 linked cases), which was selected as the final link-prediction model.

The deployed XGBoost model can interpret the portion of individual variables to each forecast cases through log-odds-based probabilities calculations. In particular, this process can be interpreted through visualization through the waterfall chart in 'xgboost expander' package of the R program, and a representative example is given in Figure 3.

The Fig. 3 is a cooperative case between France's EGIS and Indonesia's local company INDEC INNUSA in the management and technical assistance projects of the water resources sector ordered from Indonesia in 2013. In this case, the link-prediction model predicted a 60.12% (log-odds: 0.41), with a large difference in degree centrality of 2 (log-odds: 2.58), and a large ODA experience difference of 3 (log-odds: 1.59) as factors that increase the probability of cooperation. On the other hand, the large difference in the size of the main engagement project (log-odds: -1.62), the five-year difference in general experience in the construction industry (log-odds: -0.82), and the global-local partnership (log-odds: -0.31) contributed to reducing the probability of cooperation.

In summary, the greater the difference in topology (degree centrality) in the network in the case of cooperation between global and local companies, the less likely it is to cooperate with companies with similar general experience in the construction industry. In addition, the wide gap in ODA experience is also a factor that increases the chances of cooperation, and the relationship between global and local companies is a factor that reduces the probability of cooperation.

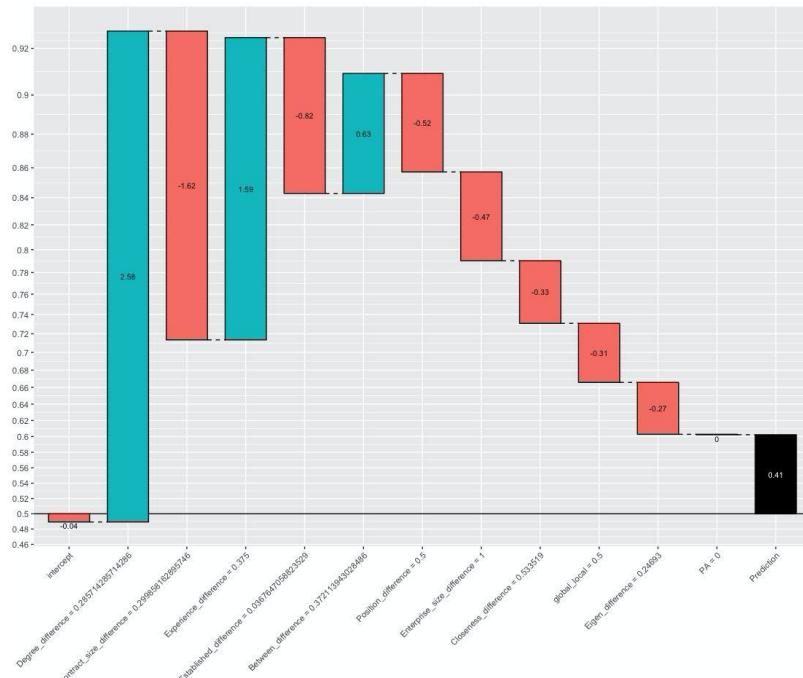


Figure 3. EGIS-INDEC Internusa cooperative case

4. CONCLUSION

This study has developed a link-prediction model with a sensitivity of 70.26% that correctly predicts 163 out of 232 actual cooperative cases, reflecting the dynamic change in the winning company network participating in the World Bank ODA project. In this process, three machine learning algorithms were used to explore suitable learning models for link-prediction, and a methodology was presented to enable E&C firms to explore appropriate business partners. In particular, this model

presented the process of deriving the probability of cooperation of individual links, which is expected to provide customized information that recommends specific partners for each firm.

However, other cases predicted by the link-prediction model showed that even if the variables were the same value, the effect on the cooperative factors changed as the values of the other variables changed. This means that detailed forecasting of individual cases is possible, but it is difficult to generalize the effects of each variable, making it difficult to provide universal information. Therefore, additional factor analyses will be conducted in the future to provide consistent information about the variables used to build the model.

ACKNOWLEDGEMENTS

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Online Multi-Task Learning and Wearable Biosensor-based Detection of Multiple Seniors' Stress in Daily Interaction with the Urban Environment

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Abstract: Wearable biosensors have the potential to non-invasively and continuously monitor seniors' stress in their daily interaction with the urban environment, thereby enabling to address the stress and ultimately advance their outdoor mobility. However, current wearable biosensor-based stress detection methods have several drawbacks in field application due to their dependence on batch-learning algorithms. First, these methods train a single classifier, which might not account for multiple subjects' different physiological reactivity to stress. Second, they require a great deal of computational power to store and reuse all previous data for updating the single classifier. To address this issue, we tested the feasibility of online multi-task learning (OMTL) algorithms to identify multiple seniors' stress from electrodermal activity (EDA) collected by a wristband-type biosensor in a daily trip setting. As a result, OMTL algorithms showed the higher test accuracy (75.7%, 76.2%, and 71.2%) than a batch-learning algorithm (64.8%). This finding demonstrates that the OMTL algorithms can strengthen the field applicability of the wearable biosensor-based stress detection, thereby contributing to better understanding the seniors' stress in the urban environment and ultimately advancing their mobility.

Key words: Online multi-task learning, wearable biosensing, stress in daily life, seniors' mobility, the urban environment

1. INTRODUCTION

Mobility (i.e., an individual's overall capability to access desired people or places [1]) is a fundamental civil right that should be maintained in the urban infrastructure [2]. However, the mobility of the senior population (i.e., people aged 65 or over) has been significantly limited mainly due to the stressful interactions with the current urban infrastructure that they suffer in their daily trips [3-5]. While seniors' physical and cognitive capabilities are impaired as a result of the natural aging process [6], many environmental barriers in the current urban infrastructure, such as steep uphill climbs, curbs without ramps, and complex traffic signage, pose excessive physical or cognitive demands on seniors, thereby inducing stress in their daily trips [3-5]. As a result, several indices of mobility such as frequency and distance of daily trips represent limitations in seniors' mobility [7]. Such limited mobility has caused diverse social issues related to seniors' health and social engagement [8-11].

To monitor and address the seniors' stress in their daily interaction with the built environment, previous approaches have mainly relied on manual surveys [12-14]. Although these survey-based approaches have contributed to identifying different types of the environmental barriers that seniors self-report, they might be limited in field applicability for several reasons. First, these methods require seniors' active participation (e.g., attending surveys and self-reporting), thereby interfering with their

daily lives. Also, the survey-based methods are generally conducted in a discontinuous and periodic manner with an interval (e.g., once a half year or once a year) so that may miss a number of environmental barriers that are time-dependent (e.g., snowy sidewalks and rain puddles on streets).

Recent advancements and the prevalence of wearable biosensors can open a door toward a new urban sensing that monitors people's stress in their daily trips. Wearable biosensors can be used as a means to less-invasively and continuously measure stress because human sympathetic nervous system aroused by the stress introverts several physiological activities such as eccrine sweat production and cardiac activity, which could be measured using physiological signals (e.g., electrodermal activity [EDA], skin temperature and photoplethysmogram) [15]. In this sense, several recent studies have proposed to apply wearable biosensors to understand people's stress in their daily lives such as driving [16-18], office work [19], field work [20], and walking [21,22]. To understand stress based on physiological signals collected by wearable biosensors, the previous studies trained and validated a machine learning classifier. Although these studies showed that wearable biosensors could be applied to identify people's stress in a naturalistic setting, there are several limitations. First, these studies applied batch-learning algorithms to create one single classifier to detect different subjects' stress [23]. Given that wearable biosensors would be applied to thousands of citizens as an urban sensing mechanism, one classifier may not be able to accurately detect the numerous citizens' stress because people's physiological response to stress can vary among individuals with different characteristics (e.g., ages, gender, body metabolism, etc.) [24]. Also, batch-learning algorithms store and use all the previous data to update the single classifier every time new data arrives, which will not be computationally practical for an urban sensing context due to a large number of subjects.

To overcome these limitations, the authors apply online multi-task learning (OMTL) algorithms [25,26]. Unlike the batch-learning algorithms that train one single classifier for the entire dataset, OMTL algorithms train multiple classifiers corresponding to the number of tasks in the dataset. At every input of each data point, OMTL algorithms update parameters of classifiers as well as the task interaction matrix that contain information about different tasks' similarity [27]. Specifically, once a data point is input from a task, OMTL algorithms first update the parameters of a classifier trained for the task. Then, other classifiers are also updated based on the input data point having similarity with the task classifier as a learning rate, which could be acquired from the task interaction matrix. The final step is to update the interaction matrix based on the similarities between newly updated parameters of different classifiers. Since OMTL algorithms learn multiple classifiers for each task (each subject in this study), more accurate detection of stress for multiple subjects can be expected. Also, the OMTL algorithms are basically the online learning algorithms that update classifiers at every input of data points. Therefore, there is no need to store and use all the previous data to update classifiers for newly arrived data. However, the feasibility of OMTL algorithms to understand people's stress from physiological signals collected by wearable biosensors in a daily trip setting has not been well studied. Although a recent study tested the OMTL algorithms to understand construction workers' stress [28], this study used the brainwave data collected by wearable-type electroencephalography sensor (EEG) that might not be applicable to people's daily lives. To fill the gap, the objective of this study is to test the feasibility of the OMTL algorithms to detect multiple seniors' stress from physiological signals collected by a less-invasive wristband-type biosensor.

2. OMTL-BASED SENIORS' STRESS DETECTION

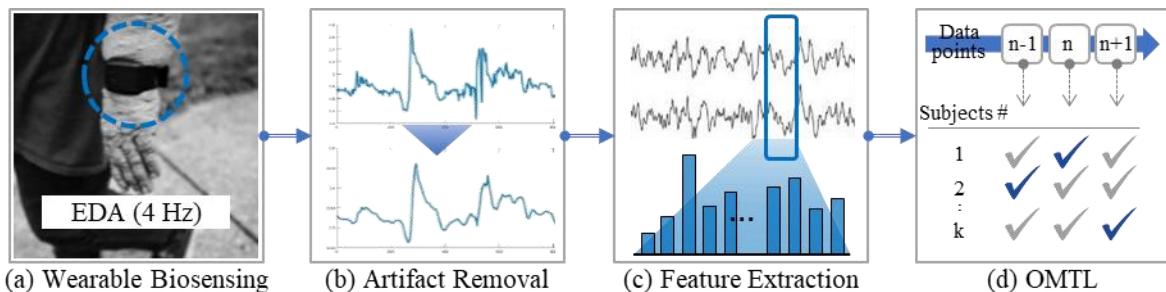


Figure 1. Steps of the OMTL and wearable biosensor-based stress detection for multiple seniors

Figure 1 shows a procedure of the OMTL and wearable biosensor-based stress detection for multiple seniors. First, multiple senior individuals' physiological signals were collected using a wristband-type

biosensor. Then, noises contained in the collected physiological signals were alleviated by applying the moving average and high-pass filter. After reducing physiological signal noises, several features were extracted in time and frequency domain to understand patterns of physiological signals. Finally, several OMTL algorithms were applied to train a model to predict multiple different seniors' stress. A more detailed explanation of each step is given below.

2.1. Wearable biosensing

As the first step, multiple senior individuals' physiological signals were acquired using a wristband-type biosensor. The authors collected EDA to measure seniors' stress. EDA shows the changes in electrical conductance of the skin in response to eccrine sweat gland activity [24]. Since eccrine sweat gland is a representative organ that well reflects arousal in sympathetic nervous system induced by stress, the EDA has been widely used to measure human stress. Also, EDA could be continuously and less-invasively collected from people's skin in daily trip contexts.

2.2. Artifact removal

Acquired EDA from uncontrolled and ambulatory settings contains several noises such as noises that come from subjects' body movements and electromagnetic fields [24,29]. Since such noises could compromise the accuracy of detecting stress by distorting values of extracted features from EDA, noise removal is a critical step for accurate detection of stress [30]. The authors applied a moving average filter to remove high-frequency noises such as noises resulting from body movements and surrounding electromagnetic fields [20]. A high-pass filter with the cut-off frequency of 0.05 Hz was also applied to suppress high-frequency noises (e.g., noises caused by variation in temperature, humidity, and impedance of sensor's electrodes) [33].

2.3. Feature extraction

To extract features, EDA was decomposed into two components-electrodermal level (EDL) and electrodermal response (EDR). EDL is a slowly changing component that includes spontaneous fluctuations of EDA [24]. Contrarily, EDR is a fast-changing component that reflects immediate body response to stress [24]. Features were extracted from both EDL and EDR [24]. As a second step, the continuous EDL and EDR were segmented into data points by a window of ten seconds length with one second moving spans. Ten-second window size was selected due to the reactivity of EDA to stress generally spans ten seconds including a latency period [20]. Eleven time domain features and three frequency domain features were extracted from segmented EDL and EDR. In this research, the features were selected from the literature on EDA-based stress identification [21,23,32,33] (Table 1). Specifically, three traditional statistics (i.e., mean, median, and standard deviation) were selected to describe the statistical characteristics of each data segment [21,23,32]. Also, three morphological features (i.e., Integral, Power, and Normalized root mean square) were defined for characterizing the signal wave shape using the following three equations (Equation 1-3) [23,32]. Two features (i.e., mean and variability of intensity overall phasic width) were also extracted to understand EDR's morphology using sparse representation [34]. The sparse representation technique decomposes EDR into multiple atoms from a pre-designed dictionary that well reflects the specific shapes of stress response in EDR [34]. In addition, three spectral power features were used to understand the different patterns in frequency domain according to the different levels of stress [23,32].

$$\text{Integral} = \sum_{n=1}^N edr(n) \quad (1)$$

$$\text{Power} = \frac{1}{n} \sum_{n=1}^N edr^2(n) \quad (2)$$

$$\text{Normalized root mean square} = \left(\frac{1}{n} \sum_{n=1}^N edr^2(n) \right)^2 \quad (3)$$

Table 1. The features extracted from EDA

Component	Type	Features
EDL	Time feature	Mean, Median, SD
EDR	Time feature	Mean, Median, SD, Integral, Power, Normalized root mean square, Mean intensity overall phasic width, Variability of intensity overall phasic width
	Frequency feature	Spectral power (0.1 to 0.2 Hz), Spectral power (0.2 to 0.3 Hz), Spectral power (0.3 to 0.4 Hz)

2.4. OMTL

The authors applied all OMTL algorithms developed to date (i.e., OMTL-LogDet, OMTL-von Neumann, and OMTL-Covariance [25,26]) to identify multiple different seniors' stress from EDA. The three OMTL algorithms have different rules for updating the interaction matrix. Here, different subjects were considered as different tasks. For benchmarking purpose, the authors compared the performance of the OMTL algorithms with two baselines. The first baseline was a traditional batch-learning algorithm. Gaussian support vector machine (GSVM) was used as the batch-learning algorithm because GSVM has demonstrated the best performance in detecting stress based on physiological signals collected by a wearable sensor in previous studies [35-37]. The authors applied GSVM in an online setting (repeat updating a classifier based on all the previous data at each input of data point) to compare its performance with OMTL algorithms. By comparing OMTL algorithms with GSVM, it would be examined whether training multiple different classifiers according to different tasks can more accurately detect stress than training one single classifier. The second baseline is the K independent task classifiers (ITL) where K different classifiers are trained according to different tasks unlike batch-learning algorithms, but there is no cross update between classifiers based on a similarity between tasks. Comparison between ITL and OMTL algorithms can show the benefits from cross update between classifiers of similar tasks.

Table 2 shows the pseudocode of the tested OMTL algorithms. OMTL algorithms jointly update parameters of classifiers (w_t) and task relationship matrix (A_t). First, $A_{t=0}$ and $w_{t=0}$ are initialized (1 in Table 2). Then, when a new data point arrives, its label is estimated using w_t (2 in Table 2). Once the estimation fails, parameters of all classifiers (w_t) are updated considering the task interaction matrix (A_t) (3a in Table 2). Then, A_t is also updated based on the newly updated w_t (3b in Table 2). The update of A_t starts after waiting for a number of rounds, which is determined based on *Epoch* because of the parameter w_t are not well formed during the initial rounds, which lead to poor estimates of A_t .

Table 2. Pseudocode of OMTL algorithms

1. $A_{t=0} = \frac{1}{K} * I_{K \times K}$ and $w_{t=0} = 0_{1 \times Km}$ and $t = 0$	K : the number of tasks
2. $L(x_t, k_t) = \text{Sign}(w_{t,k_t}^T x_t)$	x_t : data point at time t
3. If $L(x_t, k_t) \neq y_t$	k_t : task of data point at time t
a. $w_{t,i} = w_{t-1,i} + y_t A_{i,k_t}^{-1} x_t \quad \forall i \in \{1, 2, \dots, K\}$	y_t : true label of data point at time t
b. If $t \geq \text{Epoch} \times n$, then update A_t using (1), (2), (3)	$w_t = [w_{t,1}, w_{t,2}, \dots, w_{t,K}]$: parameters for all classifiers
c. Else, $A_t = A_t$	n : number of total data points
4. Else, $w_{t,i} = w_{t,i} \quad \forall i \in \{1, 2, \dots, K\}$ and $A_t = A_t$	
5. $t = t + 1$	

The authors applied three OMTL algorithms with different rule of updating task interaction matrix (A_t) as illustrated in equations (1)-(3). There are two parameters of OMTL algorithms, *Epoch* and learning rate. *Epoch* indicates the rate of waiting rounds before updating A_t . η denotes the learning rate for the A_t update. In this study, *Epoch* and η were optimized by 0.6 and $10^{-15.5}$ respectively based on the prior experimental results.

$$1. \text{ OMTL-LogDet: } A_t = \left(A_{t-1}^{-1} + \eta(w_{t-1}^T w_{t-1}) \right)^{-1}, \eta: \text{learning rate} \quad (1)$$

$$2. \text{ OMTL-von Neumann: } A_t = \exp(\log(A_{t-1}) - \eta w_{t-1}^T w_{t-1}), \eta: \text{learning rate} \quad (2)$$

$$3. \text{ OMTL-Covariance: } A_t = \text{cov}(w_{t-1}) \quad (3)$$

The test accuracy was compared among all applied algorithms. Specifically, the dataset was first undersampled for balance between classes. When the EDA data are imbalanced, which means that the number of data points in a class is much more than that of other class, the resultant classifier would be inaccurate to predict the minority class. Random permutation was also conducted because the input order of data points could affect the test accuracy. Then, the permuted dataset was randomly divided into 80% training session and 20% testing session without any overlap. All the tested algorithms were applied to train and update classifiers using data points sequentially taken from the training session. At every input of each data point, the updated classifiers' test accuracy was measured based on the testing session. After completing the update using all the data points, the test accuracy was averaged. This 'undersampling-permutation-holdout test' procedure was repeated 20 times and reported test accuracy was calculated by averaging the 20 trials to make sure that the results reflected the general performance of the tested algorithms, not the performance in a randomly undersampled, generated and permuted subset of data.

3. FIELD DATA COLLECTION

The ten mobile senior subjects were recruited for the field data collection from Clark East Tower senior apartment located in Ypsilanti Township, Michigan. Data collection protocol was approved by the University of Michigan Institutional Review Board (IRB00000245). The informed consent forms were distributed to make all the subjects informed about the anonymity of data collection and their rights. They were also asked to report their mental health issues. None of the subjects reported any mental issues that can affect stress detection based on physiological signals. To account for variability of senior population in physical capability, five seniors depending on a walker or scooter as an assistive device were included in the subject group. Table 3 summarizes the subjects' demographic information.

Table 3. Subjects' Demographic Information

Item	Age (years)	Height (cm)	Weight (kg)	Assistive Device Use
Mean (SD)	68.1 (5.79)	168.3 (8.7)	81.7 (8.4)	Walker 4, Scooter 1, No use 5

In the field data collection, the subjects were asked to walk over a predesigned route on which there was a series of 12 environmental barriers, including curbs without ramps and unpaved sidewalks (Figure 2). The series of environmental barriers were determined by authors based on previous studies that identified the typical environmental barriers where seniors get stressed in the current urban infrastructure [4,39]. While the subject passed along the route, their EDA signal was collected at 4 Hz sampling rate using a wristband-type biosensor. During the experiment, participants were video recorded for labeling purposes. After subjects completed the route, the researchers surveyed whether the subjects actually became stressed or not on each environmental barrier in a binary manner (i.e., stress or non-stress). To reduce the recall bias, the authors showed pictures of all the environmental barriers. After the data collection, the collected EDA signals were labeled into stress or non-stress based on the result of the stress survey as well as the recorded video. The authors excluded EDA signals collected when the subjects experienced unintended stressors such as interaction with vehicles or other people and loss of balance while walking. Then, EDA signals acquired while subjects passed over environmental barriers that they confirmed as a stressor in the survey were labeled as "stress."

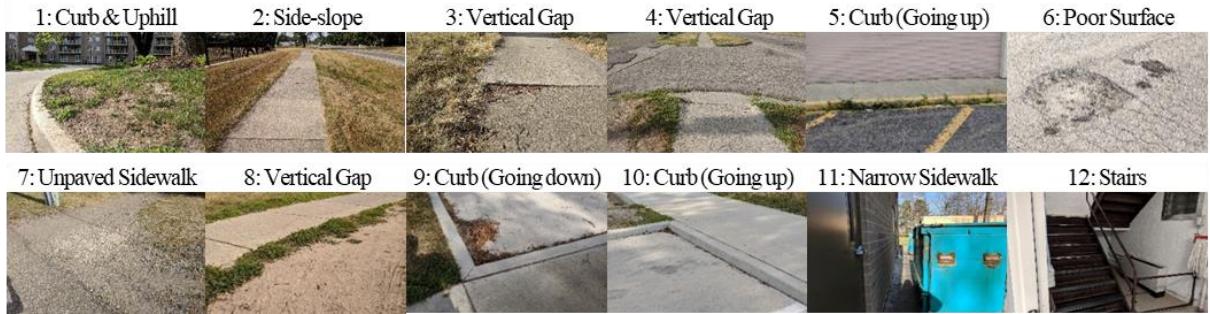


Figure 2. Environmental barriers in data collection

4. RESULTS AND DISCUSSIONS

As a result of field data collection, 23,627 data points were collected. Among them, 1,936 data points were labeled as stress, and other 21,691 data points were labeled as non-stress. Due to such imbalance, balanced 3,872 data points (the whole 1,936 stress data points, and 1,936 undersampled non-stress data points) were generated by undersampling as a first step of the ‘undersampling-permutation-holdout test’ procedure. The confusion matrices for different algorithms are reported in Table 4. Three performance metrics were used: accuracy, precision, and recall. Accuracy indicates the tested algorithms’ overall performance to correctly classify whole samples. Precision means the performance to exclude actual “non-stress” samples from “stress” class, while recall is the performance to include actual “stress” samples in “stress” class.

The batch-learning algorithm (GSVM) showed the lowest test accuracy (64.8%). Compared with the batch-learning algorithm, ITL performs better with a prediction accuracy of 70.6%. This result shows that independently training ten different classifiers for ten different subjects will lead to more accurate stress detection. This may be explained by the fact that the one classifier trained by the batch-learning algorithm could not enough account for the ten subjects’ different physiological reactivity to stress.

Table 4. Confusion matrices of the tested algorithms

Batch-learning (GSVM)					
Accuracy: 64.8%		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	28.2%	13.7%	67.4%	57.1%
	Low-Risk	21.8%	36.3%		
Independent Task classifiers (ITL)					
Accuracy: 70.6%		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	39.6%	18.7%	68.0%	78.7%
	Low-Risk	10.7%	31.0%		
OMTL LogDet					
Accuracy: 75.7%		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	38.3%	12.0%	76.2%	75.6%
	Low-Risk	12.4%	37.3%		
OMTL von-Neumann					
Accuracy: 76.2%		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	38.2%	11.9%	76.2%	76.3%
	Low-Risk	11.9%	38.0%		
OMTL Covariance					
Accuracy: 71.2%		True Class		Precision	Recall
		High Risk	Low Risk		
Predicted Class	High-Risk	39.4%	18.0%	68.6%	78.5%
	Low-Risk	10.8%	31.8%		

All the applied OMTL algorithms brought higher test accuracy (75.7% for OMTL-LogDet, 76.2% for OMTL-von Neumann, and 71.2% for OMTL-Covariance) than both ITL and the batch-learning algorithm. It indicates that cross update between different classifiers, which the OMTL algorithms conducted based on the similarity between their tasks, helps train all the classifiers, thereby bringing better test accuracy than training each classifier independently. Among different OMTL algorithms, test accuracy of the OMTL von-Neumann and OMTL LogDet were higher (76.2% and 75.7% respectively) than OMTL Covariance. This result coincides with the result of [28], which applied OMTL to detect stress based on EEG signals. Given that OMTL Covariance showed comparable performance to other OMTL algorithms in tasks using text data [26], the better performance of OMTL von-Neumann and OMTL LogDet in this study may be because of the more robust performance of these two algorithms when dealing with outliers in physiological signals such as EDA and EEG due to the exponential and reciprocal updating [28].

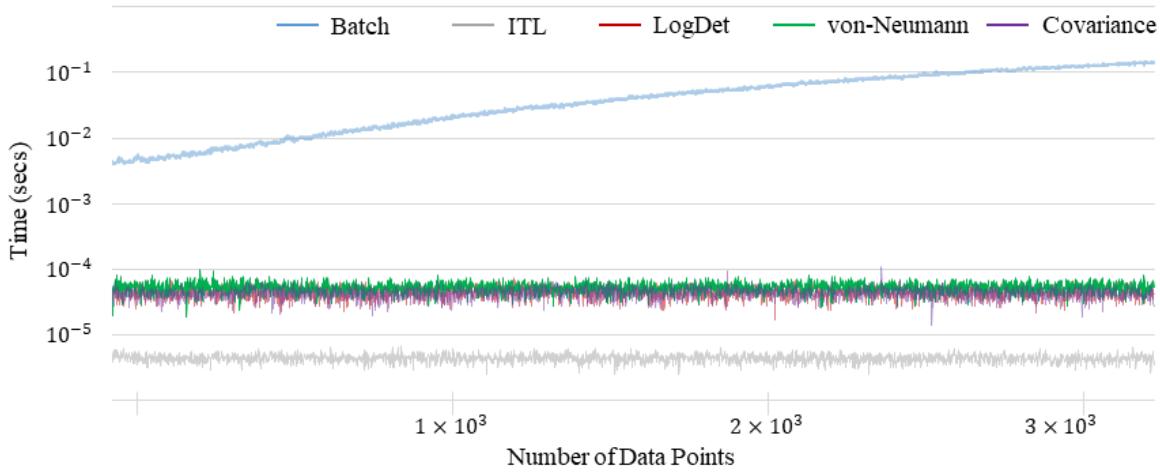


Figure 3. Computational time of tested algorithms

In addition to accuracy, all the tested algorithms' computational time was examined to compare computational complexity. Figure 3 shows the computational time of every update. The reported computational time was calculated by averaging 20 times of trainings. As a result, the traditional batch learning algorithm in an online setting spent significantly higher computational time than the OMTL algorithms and ITL. Also, the batch learning algorithm's computational time increased with every update while those of OMTL algorithms stayed within a certain range. This can be explained by the fact that the batch learning algorithms require all the previous data points for each update, and the number of data points in the batch increased by one at every update. Given that data size in urban sensing contexts is, in general, far bigger than the data collected in this study, such increase in computational complexity according to the number of data points indicates that the batch learning algorithms might be less practical in urban sensing contexts. ITL showed the least computational complexity, which can be expected because ITL does not update interaction matrix unlike OMTL algorithms. There was no significant difference among OMTL algorithms.

The results of this study indicate that the OMTL algorithms can more accurately detect multiple seniors' stress from EDA collected by a wristband-type biosensor in a daily trip setting than traditional batch-learning algorithms. Also, OMTL algorithms showed less computational complexity than the traditional batch learning algorithm. Since the OMTL algorithms do not need to store and use all previous data for updating their classifiers, they are less computationally complex than traditional batch-learning algorithms. Lower computational cost and time of these algorithms make them a better fit for the urban sensing to extensively identify seniors' stress in the urban environment.

Finally, a number of important limitations need to be considered. First, the simple perceptron was used for as a base learning algorithm (3a in Table 2) in the OMTL algorithms in this study. More sophisticated parametric algorithms such as the kernel perceptron have been developed to train a classifier in an online setting [39]. The future studies will additionally apply such algorithms for the classifier update to increase the performance of OMTL algorithms. Second, this study was conducted based on a small sample of senior population (i.e., 10 subjects). Given that the stress detection would be applied in urban scale, how the proposed OMTL-based stress detection performs with a larger sample

of senior population needs to be examined in a future study. Specifically, the sample of senior population should exhibit considerable variability in age, physical conditions, and assistive device use to make sure generalization of the proposed stress detection. Third, although only different subjects were dealt as different tasks in this study, different outdoor conditions such as temperature and a level of humidity should be considered as different tasks as well because EDA signal's reactivity to stress varies according to such outdoor conditions [24]. Future research is needed to examine whether OMTL algorithms can accurately detect stress under different outdoor conditions as well as different subjects. Lastly, although OMTL algorithms can significantly improve the practicality of wearable-based stress detection by working without storing and using all the previous data, still data from all users needs to be labeled, which is another critical hurdle to apply wearable-based stress detection in urban sensing contexts. To address the labeling burden, how stress detection models can be applied for a new person who is not involved in training should be studies in future research.

5. CONCLUSION

The traditional batch-learning algorithms could not be applied for the urban sensing to detect thousands of seniors' stress in daily trips because they depend on one classifier and require much computational power to store and re-use all the previous data for updating the classifier. To address this issue, the authors tested the feasibility of OMTL algorithms to detect stress based on different seniors' EDA signals collected by a wearable biosensor in a daily trip setting. Specifically, EDA signals labeled as stress or non-stress were collected from ten senior subjects while experiencing a predesigned route on which there was a series of environmental barriers. Based on the EDA signals, the test accuracy of three OMTL algorithms were compared with a traditional batch-learning algorithm (i.e., GSVM). As a result, all OMTL algorithms showed higher test accuracy (75.7% for OMTL-LogDet, 76.2% for OMTL-von Neumann, and 71.2% for OMTL-Covariance) than the batch-learning algorithm (64.8%). This result indicates that the OMTL algorithms are more feasible than the batch-learning algorithms to accurately detect multiple seniors' stress in an online manner based on EDA collected by wearable biosensors in a daily trip setting. This finding can improve the field applicability of the wearable biosensing-based stress monitoring method, thereby contributing to monitoring and addressing seniors' stress in their daily trips, and ultimately advancing their outdoor mobility.

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XVI. INTELLIGENT CONSTRUCTION AUTOMATION I (F1)

Image Processing-based Object Recognition Approach for Automatic Operation of Cranes

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Abstract: The construction industry is suffering from aging workers, frequent accidents, as well as low productivity. With the rapid development of information technologies in recent years, automatic construction, especially automatic cranes, is regarded as a promising solution for the above problems and attracting more and more attention. However, in practice, limited by the complexity and dynamics of construction environment, manual inspection which is time-consuming and error-prone is still the only way to recognize the search object for the operation of crane. To solve this problem, an image-processing-based automated object recognition approach is proposed in this paper, which is a fusion of Convolutional-Neutral-Network (CNN)-based and traditional object detections. The search object is firstly extracted from the background by the trained Faster R-CNN. And then through a series of image processing including Canny, Hough and Endpoints clustering analysis, the vertices of the search object can be determined to locate it in 3D space uniquely. Finally, the features (e.g., centroid coordinate, size, and color) of the search object are extracted for further recognition. The approach presented in this paper was implemented in OpenCV, and the prototype was written in Microsoft Visual C++. This proposed approach shows great potential for the automatic operation of crane. Further researches and more extensive field experiments will follow in the future.

Key words: automated object recognition, vertex-based determining model, image processing, automatic cranes

1. INTRODUCTION

Recent years, with the rapid development of information technology, automatic construction has attracted more and more attention in construction industry. As the most essential components on site with large moving and heavy loads, cranes are involved in all kinds of construction tasks ranging from assembling prefabricated components to hoisting construction materials like rebars and timbers [1]. Therefore, considering efficiency and safety, cranes should be more automated in the future.

Automatic crane is not a new problem in construction industry, previous researches including: 1) the selection of crane type [2] [3] [4], 2) the location identification and optimization of mobile crane [5] [6] [7], 3) lifting path planning [8] [9] [10], 4) coordination of multiple cranes [11] [12] [13], 5) the simulation and visualization for crane operation [14] [15]. We can find that there are few researches about the automatic recognition of crane which is not only the base of automatic crane, but also necessary to achieve fully automatic level, assuming the initial position of the search object for cranes is given [16]. While in practice, limited by the complexity and dynamics of construction environment,

conventional manual inspection is the only way on site to determine the original position of the search object, making the operation of crane time-consuming and error-prone.

Recent years, the rapid developments of information technology have provided us with new sensor-based solutions (e.g. three-dimensional (3D) laser scanning and image processing) to realize automated object recognition of crane. And image processing is faster and cheaper with acceptable precision than 3D laser scanning. Besides, 3D laser transmitter is usually loaded on Unmanned Aerial Vehicle (UAV) which however is not allowed to use in some real cases due to the limitation of local regulations, considering government security and privacy protection. Therefore, image processing is selected as the basic automation recognition technology in this research.

2. LITERATURE REVIEW

In order to realize automatic object recognition of crane, its definition should be clarified at first. Although object recognition is a basic problem that has been extensively mentioned in previous research, recognition approaches are different in specific contexts (e.g. computer vision [17] [18] [19], robotics [20] [21] and autonomous driving [22] [23]). In general, object recognition in previous research is defined as the location of a desired object in a scene [24] including: 1) the detection and classification in 2D image, 2) 3D location of the search object with orientation, motion, pose and structure, based on a prior knowledge of the search object including its shape, color and other features.

However, considering the following differences between construction and the applications mentioned above: 1) most recognition targets in construction are artificial objects with similar concrete textures and regular shapes; 2) the 3D location with exact pose of the search object is necessary to determine the following lifting path planning of the crane; 3) except for visible features mentioned above (e.g. texture), other invisible features such as weight [5] are also vital to automatic lifting. Based on this, the object recognition of automatic cranes in this research can be defined as the fusion of object detection in 2D image and the 3D location of the search object with determined visible features (e.g., location, pose, size, and texture) and invisible features (e.g., weight).

Traditionally, feature-based object detection methods are prevalent because of their simplification, speediness and accuracy. Based on the different types of detection template, existing feature-based detection methods can be classified as Histogram-of-Oriented-Gradient (HOG)-based [25], texture/color-based [26] [27], shape-based [28] [29] [30] and scale/affine-invariant feature-based [31] [32]. However, these methods are not robust enough in practice due to the unavoidable effects of the changing environment on feature extraction. In addition, most feature extraction algorithms applied (e.g. Canny operator [33] and Hough detection [34]) are unadjustable image processing in practice with fixed thresholds, making it unsuitable to the complicated construction environment. Although traditional object detection methods in 2D image have shown great potential in feature extraction with speediness and accuracy, they are not robust enough to resist the effects on feature extraction caused by the changing external circumstances, limited to the fixed thresholds.

Recently, the rapid developments of machine learning and deep learning have also promoted the application of Computer Vision (CV), especially Convolutional-Neutral-Network (CNN)-based object detection in construction, as shown in Table 1. According to the research, previous CNN-based detection researches mainly focus on damage/defect detection [30] [35] [36], object classification [37] [40] and workers' activities recognition [38] [39] on site, few exploiting the detection results for further object location in 3D, although it has shown great potential in extracting the search object from complicated 2D backgrounds.

Table 1. CNN-based detection researches in construction

Year	Objective	Applied detection algorithms	Results	Paper
2010	Concrete columns detection for automated bridge inspection	Artificial neural network for concrete material recognition, Canny operator, Hough transform	Accuracy of 89.7%	[30]
2015	Changes detection in tunnel lining	CNN	-	[35]

2018	Detecting healthy surface regions of bridges	Sliding window approach, GoogleNet network	Accuracy of 82.8%, a search space reduction of 90.1%	[36]
2018	No-hardhat-use detection	Faster R-CNN	Precision more than 90%	[37]
2018	Recognizing workers' activities	Two-stream convolutional networks	An average accuracy of 80.5%	[38]
2018	Workforce activity assessment for steel reinforcement fixers	An improved CNN	An average accuracy of 85%	[39]
2018.5	Detect the presence of workers and excavators	Improved Faster R-CNN	As a high level of accuracy (91% and 95% respectively)	[40]

In conclusion, no matter feature/non-feature-based or CNN-based, all object detection approaches mentioned above only classify and detect objects of interest in 2D images, which means that spatial location of the search objects with exact pose is little considered in previous researches. Hence, a novel and robust object recognition approach is proposed in this paper, which exploits the synchronized relationship of 3D spatial location and the 2D detection results of CNN-based and traditional object detection from sensed real-time data to locate the search object with exact pose, more accurate visible features and invisible features. The primary objective of the approach presented in this research is to examine the feasibility of image-processing-based object recognition approach for automatic crane.

3. RESEARCH METHOD

According to the above definition of object recognition for construction cranes and the review of previous research, the following two issues need to be considered seriously so as to develop an appropriate object recognition approach.

3.1. The effects of background and the occlusions of other objects

On-site construction environment is always chaotic with not only the search objects, but also the unsearch objects and other moving workers that may produce occlusions and reduce the efficiency of object recognition. Therefore, how to eliminate the effects of backgrounds and the occlusions of other objects is the first fundamental problem to solve. In this research, considering that 5 fps speed of Faster R-CNN can almost meet the speed requirements of on-site object recognition with acceptable accuracy, Faster R-CNN is selected to realize the basic 2D detection of the search object from complicated backgrounds for further image processing.

3.2. Unknown pose and quantity of the search objects

Object recognition systems genuinely assume that the pose and number of the search objects are a prior unknown knowledge, and the computational complexity used to be proportional to the total quantity of the search objects in traditional recognition methods [21]. Therefore, Faster R-CNN is used to detect the search object individually each with single bounding box, and then a circular image process including simple and efficient Vertex-based determining models is performed to spatially locate the search object with pose.

According to the basic problems proposed above, our approach can be divided into three parts, and Figure 1 depicts the whole flowchart:

1) Real-time information collection of the search object by the chosen sensor (e.g. stereo camera) including synchronized 3D coordinates, image pixels and color information. And then for the retrieved 2D image, Faster R-CNN is selected to segment each object of interest from complicated background;

2) Circular image processing including Canny detection, Hough transformation, endpoints clustering analysis and Vertex-based determining model is performed until the extracted results satisfy the Vertex-based determining model;

3) Features extraction including centroid coordinate calculation, size calculation and color extraction is based on the range image fusing the retrieved 2D image and 3D coordinates of point clouds.

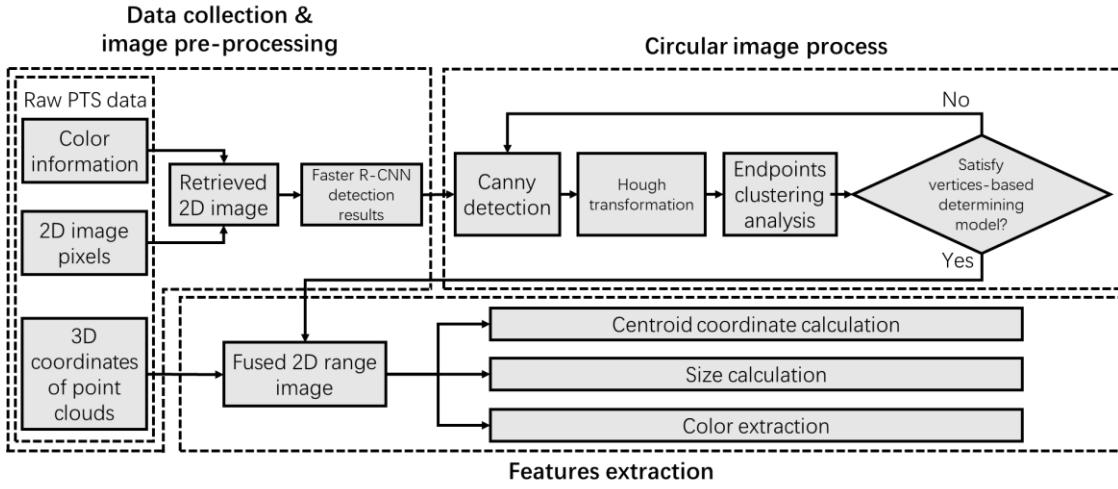


Figure 1. Overview flowchart of the proposed recognition approach

4. OBJECT RECOGNITION APPROACH

To describe the approach used clearly, cuboid-shape lifting objects (such as precast columns and slabs), which are common on construction sites, are used as the experimental prototype. Object recognition of automatic crane in this research is the combination of 2D detection and 3D location which however is based on the image detection results. According to the theory of solid geometry, the spatial location of a cuboid with exact pose can be determined, assuming that at least three specified mutually perpendicularly intersecting line segments are given. These specified lines at the same time intersect at one vertex (see Figure 2(a)) or two vertices (see Figure 2(b)). In another word, as long as the image processing results, the extracted vertex groups, satisfy our proposed Vertex-based determining models, the search object can be uniquely located in 3D space.

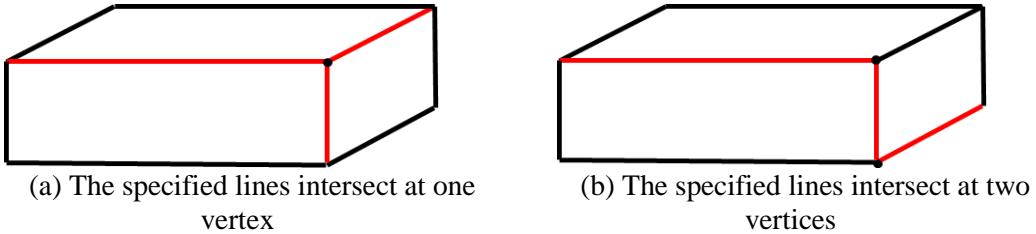


Figure 2. Specified mutually perpendicularly intersecting line segments with vertices to uniquely locate a cuboid in 3D space

4.1. Data collection and image preprocessing

Bumblebee series camera is a multi-view stereo vision component for fast stereo reconstruction developed by FLIR System Inc. Considering its accuracy and stability, it is selected in this research to collect real-time raw depth data of the scene, saved as PTS files where (x, y, z) represent 3D spatial coordinates, (u, v) represent 2D image pixels and (R, G, B) represent pixel color information. Because original images generated by single left or right shots don't contain necessary 3D information (e.g. 3D spatial coordinates), 2D images should be firstly retrieved from the collected raw depth data (u, v, R, G, B) so that the retrieved image is matched with 3D spatial coordinates (x, y, z) , as shown in Figure 3(a).

The backgrounds of the search object in the retrieved 2D image are usually complicated because of great turbulences generated by piles of materials, running machines and moving workers. As the computational complexity of image processing and feature extraction is proportional to the interference of background, the search object should be segmented from background to decrease the image size to process. Considering this problem, CNN-based object detection is applied in our research to detect the search objects from complex backgrounds before image processing. And Faster R-CNN is finally selected because of its high processing speed and detection accuracy. And the Foreground detection result of the trained Faster R-CNN is shown in Figure 3(b), with a learning rate of 0.0003, accuracy of the model finally reaching 93.3%.



(a) Retrieved 2D image



(b) Foreground detection result of Faster R-CNN

Figure 3. 2D image retrieved from PTS file and foreground detection result of Faster R-CNN

4.2. Image processing

Figure 4 depicts the circular image processing of which the inputs are the foreground detection results of Faster R-CNN. The fragments of the detected bounding boxes are then orderly processed by Canny detection, Hough transformation and Endpoints clustering analysis, to obtain edge contours, line segments with endpoints and vertex groups. As long as the extracted vertex groups satisfy any of the proposed vertex-based determining models, the search cuboid can be uniquely located in 3D. Otherwise it will go back to Canny Detection with adjusted threshold until the extracted vertex groups satisfy the presented models.

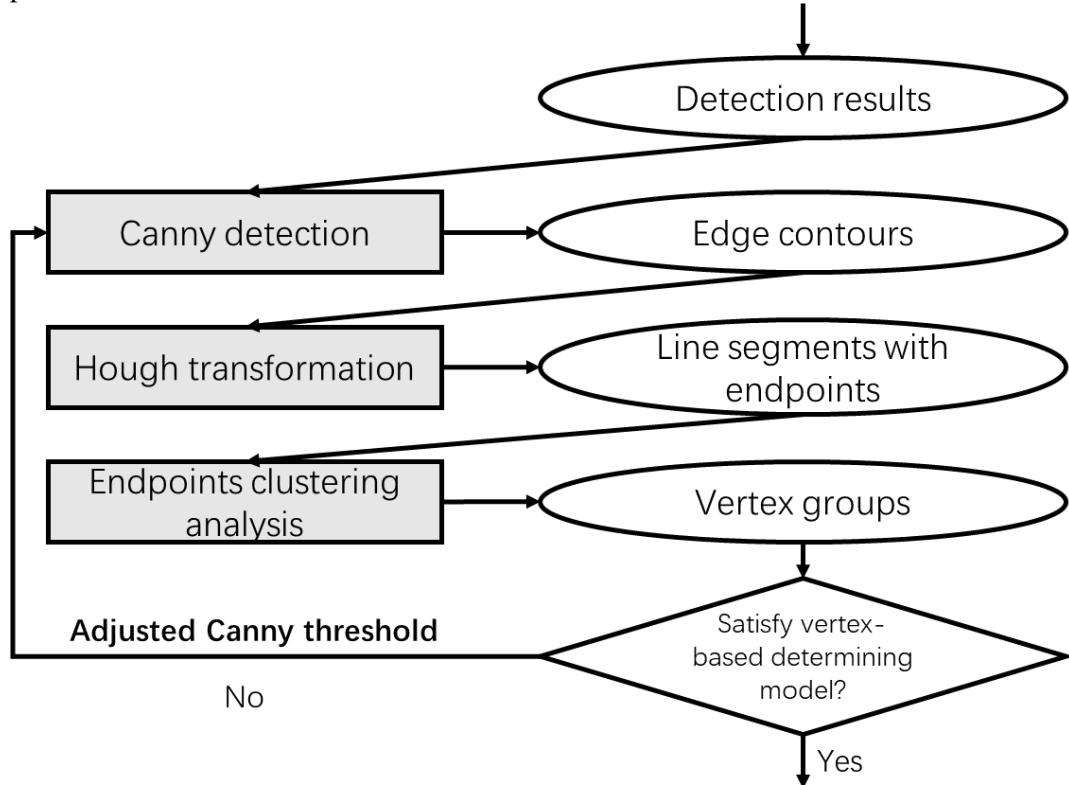


Figure 4. Circular image processing

4.2.1. Canny detection

Canny edge detection operator was proposed by Canny [41] in 1986 to obtain the extreme points of image gradient, which are possible edge contours. Based on the obtained extreme points, the true edge contours of the search objects are detected more accurately by non-maximum suppression and double threshold detection. However, two obvious limitations exist in original Canny algorithm—

- 1) The surface textures of the search objects left in bounding box affect the edge detection results;
- 2) Fixed Canny threshold for different recognition objects in all circumstances shows weak robustness.

In order to solve the problems above, clustering points which probably are textures instead of edges are detected and eliminated. As shown in Figure 5, the improved Canny with automatically adjusted threshold shows high potential in eliminating the texture contours of the search objects to obtain more accurate edge contours of the search objects. And then a circular image processing from Canny

Detection, Hough Transformation, Endpoints clustering analysis to Vertex-based determining model is presented, with adjusted Canny threshold according to the processing result until the processed vertex groups satisfy the determining models.

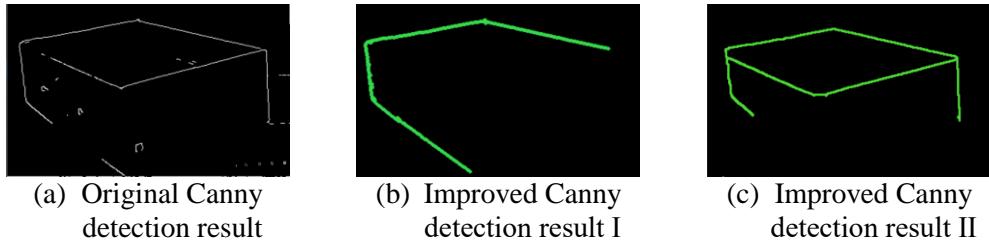


Figure 5. The comparison of edge contours detection results between Canny and improved Canny

4.2.2. Hough transformation

It should be noted that the edge contours extracted by Canny above actually are a series of contour points with extremely close distances, so these detected edge contours are not real line segments. Considering this, by transforming the detection problem of the given curve in the original image into the search of peak point in the special parameter space, Hough transform is adopted to extract the line segments information contained in these contour points. Therefore, through Hough transformation, the edge contours extracted by Canny can be transformed into corresponding line segments and corresponding endpoints with 2D image pixels (u, v). And based on the synchronized relationship between 3D spatial coordinates and 2D image pixels in PTS files, the 3D spatial coordinates (x, y, z) of these endpoints can also be further determined. Table 2 presents the detailed 3D information of a line segment extracted by Hough transformation.

Table 2. The detailed 3D information of the extracted line segments

		x	y	z	u	v
Line i	Point 1	$x_{i,1}$	$y_{i,1}$	$z_{i,1}$	$u_{i,1}$	$v_{i,1}$
	Point 2	$x_{i,2}$	$y_{i,2}$	$z_{i,2}$	$u_{i,2}$	$v_{i,2}$
	Spatial direction vector (Δ)	$\Delta x_i = x_{i,2} - x_{i,1}$	$\Delta y_i = y_{i,2} - y_{i,1}$	$\Delta z_i = z_{i,2} - z_{i,1}$	-	-
	Length of Euclidean distance (E)	$E_i = \sqrt{\Delta x_i^2 + \Delta y_i^2 + \Delta z_i^2}$				-

The ideal transformation result of Hough is that the extracted line segments with endpoints are the exact edges with vertices of the search object. In this case, adjacent edges of the search object intersect at the vertices, which means that the extracted adjacent line segments should also intersect at their endpoints. However, effected by all kinds of image noise, these extracted line segments in fact do not coincide exactly with the true edges of the search object, with a few deviations between the endpoints and the actual vertices. Therefore, the extracted adjacent line segments do not exactly intersect at their endpoints. To solve this problem, endpoints clustering analysis is performed next to identify the possible intersection relation of these line segments, by merging the endpoints of which the distances is within the pre-set distance threshold.

4.2.3. Endpoints clustering analysis

Based on the extracted line segments and endpoints of Hough Transformation, clustering analysis is performed to calculate the distances between all endpoints of two line segments, by comparing the calculated distances with the pre-set distance threshold D. If the distance is less than or equal to D, the two endpoints are regarded as a clustering point, where two corresponding line segments may intersect. In another word, the clustering point is probably a vertex of the search object. Otherwise, it can be inferred that the corresponding line segments do not intersect with each other. As shown in Figure 6, for the endpoints clustering analysis of two line segments each containing two endpoints individually (e.g. Line i and Line j), there are four groups of endpoints relationships in total to analyze:

- 1) the relationship between Line i-Point 1 and Line j-Point 1;

- 2) the relationship between Line i-Point 1 and Line j-Point 2;
- 3) the relationship between Line i-Point 2 and Line j-Point 1;
- 4) the relationship between Line i-Point 2 and Line j-Point 2.

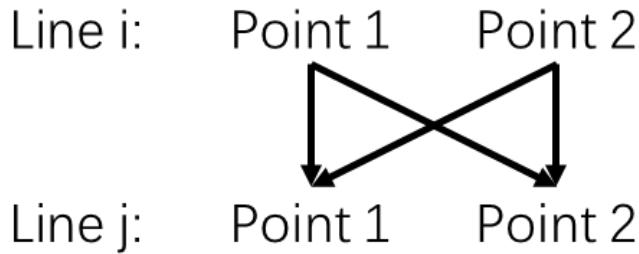


Figure 6. The endpoints clustering analysis of two line segments

The clustering point judgment of two endpoints is based on their Euclidean distance. For example, $E_{i1,j2}$ represents the Euclidean distance between Line i-Point 1 ($x_{i,1}, y_{i,1}, z_{i,1}$) and Line j-Point 2 ($x_{j,2}, y_{j,2}, z_{j,2}$) :

$$E_{i1,j2} = \sqrt{(x_{i,1} - x_{j,2})^2 + (y_{i,1} - y_{j,2})^2 + (z_{i,1} - z_{j,2})^2} \quad (1)$$

If $R_{i1,j2}$ is less than the pre-set distance threshold D (D=0.03 m in this research, which means that endpoints with Euclidean distance ≤ 0.03 m can be regarded as a clustering point), Line i-Point 1 and Line j-Point 2 are a group of clustering point and their information will be recorded. Otherwise, Line i-Point 1 and Line j-Point 2 are not clustered, and the next group of endpoints will be calculated and judged. In this way, clustering point judgment of Line i and Line j is performed on four groups of endpoints relationships in turn. As long as any calculated European distance of the four groups is less than D, it can be inferred that Line i and Line j intersect at the corresponding clustering point (the same vertex group). Otherwise, Line i and Line j don't intersect.

4.2.4. Vertex-based determining model

According to the theory of solid geometry, at least three mutually perpendicular intersecting line segments are needed to uniquely determine the spatial location of the search object, including the following two situations:

- 1) Three intersecting line segments are perpendicular to each other (see Figure 2(a));
- 2) Three line segments intersecting at two different vertices are perpendicular to each other (see Figure 2(b)).

Combining with the vertex groups generated by endpoints clustering analysis, the following two vertex-based determining models are proposed.

4.2.4.1 Model I

For the first situation, the search problem of three intersecting line segments can be converted to the search of a vertex group at which more than three line segments intersect, that is to say, the aggregation degree of the selected vertex group ≥ 3 . As for the judgment problem of these line segments intersecting vertically, it can be further converted to determining whether the three line segments containing the selected vertex are perpendicular to each other. Besides, spatial direction vectors Δ of the line segments (see Table 1) can be used for determining whether two line segments (e.g. Line i and Line j) intersect vertically. For example, if

$$\Delta x_i * \Delta x_j + \Delta y_i * \Delta y_j + \Delta z_i * \Delta z_j = 0 \quad (2)$$

Considering the experimental error and measurement error, this condition can be relaxed to

$$|\Delta x_i * \Delta x_j + \Delta y_i * \Delta y_j + \Delta z_i * \Delta z_j| \leq 0.05 \quad (3)$$

It can be inferred that Line i and Line j are perpendicular to each other. Otherwise, Line i and Line j are not perpendicular.

4.2.4.2 Model II

As for the second situation, the search problem of three line segments intersecting at two different vertices can be converted to the search of a line segment with both endpoints substituted with clustered

vertex groups. And the judgment problem of three line segments intersecting vertically can also be further converted to calculating the spatial direction vectors Δ of the selected line segments (see Formula 3).

4.3. Feature extraction

Through image processing, three specified mutually perpendicularly intersecting line segments are extracted as edges which can help to uniquely locate the search object in 3D space. And apart from location, other features including size and color are also necessary for the recognition of the search object. Based on the extracted three specified line segments above, the centroid coordinate of the search object, as the original position for the object to hoist, can be calculated according to triangular rule, and the sizes (length, width and height) are also determined at the same time. As for color, the effects of light on color extraction are considered and eliminated by white balance with satisfactory results.

5. CONCLUSION

An image-processing-based automated object recognition approach for automatic crane is presented in this research. The search object is firstly detected with bounding box from the complicated backgrounds on the retrieved 2D images by Faster R-CNN, which is trained and validated by a collected dataset with accuracy of 93.3%. Based on the detection results, a circular image processing including different object processing technologies (Canny detection, Hough transformation and Endpoints clustering analysis) is performed to extract all vertex groups of the search object. If the extracted vertex groups satisfy any of the two proposed Vertex-based determining models, the search cuboid is uniquely located in 3D with exact pose. Otherwise it will go back to Canny detection with adjusted threshold, until the extracted vertex groups satisfy the proposed models. Then three vital visible features of the search object including centroid coordinate, size and color can be further extracted.

However, there are still some limitations need to be improved in future research:

- 1) Decrease the effects of light on texture extraction. Due to the differences in light sources, weathers and shooting times, texture/color of the same search objects in different circumstances may be quite different from each other, with the accuracy of color extraction results decreased.
- 2) The address of invisible attributes. Except for visible features (e.g. color and size), other invisible attributes of the search object (e.g. weight) are also necessary for the automatic lifting of crane, which however are stored in IFC scheme of BIM models and unavailable directly by image processing technologies.

Although this proposed approach shows great potential for the automatic operation of crane, further researches and more extensive field experiments need to follow in the future.

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Measuring productivity improvement by Machine Guidance through work sampling in earthwork

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Abstract

This paper proposes a study measuring productivity improvement by using a type of technology called “Machine Guidance” through work sampling in earthwork. Earthwork is the activity typically on the critical path, indicating that productivity for the activity is critical for managing schedule on time. Thanks to the development of sensing and information system technologies, productivity for earthwork has been improved. While there have been many studies investigating the application of a certain type of technology to earthwork, few studies have measured the productivity improvement and presented how the technology leads to productivity improvement. Based on the thorough literature review, it is hypothesized that Machine Guidance contributes to improving productivity of earthwork by reducing indirect workhours spent for information waiting and inspection. In addition to the literature review, this paper presents a research model to test the hypothesis by using the work sampling technique. By proving and quantifying the productivity improvement from the technology use, this study can help practitioners justify the investment for technology use, which will contribute to the deployment of technology and more effective execution of earthwork.

Key words: Machine guidance, Productivity, Work sampling, Measurement method

1. INTRODUCTION

Earthwork is the process of moving large amounts of materials such as soils and rocks through excavation, transportation, and filling. As a basic activity of all civil and building construction projects, earthwork is typically on the critical path that has a great impact on managing construction projects. As activities in earthwork are typically equipment-driven, performance of earthwork highly depends on how equipment for the activities is utilized [1]. With the development of technologies such as sensors, machinery, and information technologies, performance of earthwork has been improved in terms of productivity, safety, and equipment operation and maintenance [2].

Various types of technologies have been applied to earthwork. For example, Chi and Caldas (2012) investigated the 3D object tracking and identification technologies to monitor any safety violations for earthmoving activities which are conducted in dynamic circumstances [3]. Azar and Kamat (2017) discussed that remote control and autonomous operation of earthmoving equipment are important areas for the future research studies [2].

This study investigates a type of technology called Machine Guidance (MG). The technology uses multiple sensors and information systems to enhance the utilization and operation of excavators by providing visual guides to operator. For the slope excavation, an operator of excavation equipment needs a surveyor who checks the level and makes sure that the slope is cut as designed. In addition, the slope excavation should be inspected by construction supervision whether the work is performed to the planned level during excavation [4]. If the supervisor does not check the work right away, the operator should wait, which is time-consuming without adding any value. MG provides information about the slope in terms of vertical and horizontal visuals to the operator. Thus, for the operator of equipment with MG, there is no surveying required. In addition, the operator can move to the neighborhood area for additional work without inspection by the supervisor.

Several studies investigated MG and showed the productivity improvement in terms of quantity. For example, Azar et al. (2015) showed 19% to 23% productivity improvement for excavators from two case studies [5]. The study also presented that MG contributed to reducing the need for surveying work hours by 30% to 5%. Another research found that equipment with MG worked 38.3% of additional volume for 4 working days although the increase per a day varied depending on the driver's competence to MG and the complexity of the excavation terrain [4].

While there have been a number of studies demonstrating the productivity improvement by MG, most of the studies showed the productivity improvement by increased quantity. Studies showing that quantity per unit time has increased by MG can validate that MG contributes to productivity improvement. However, they cannot show how such productivity improvement has been achieved. In order to address the issue, it is necessary to measure the productivity improvement by work sampling. Work sampling measures time for an operator to perform activities and classified time into three types: direct, support (indirect), and delay (idle). As MG provides information that operators need, their indirect work hours which are spent for operations other than excavation such as surveying, stakeout, and grade check can be reduced. The reduced indirect work hours can lead to more direct work hours, time directly spent for excavation work. As more direct work hours indicate that excavators can spend more time for excavation work, quantity per unit time should increase. Indeed, classifying on-site labor's work hours into categories such as direct, indirect and idle helps to measure the time expenditures of workers easily, and identify the productivity inhibitors that must be reduced to let workers have more time for direct work [6].

This study investigates the productivity improvement by MG on excavators by work sampling. The time excavators spent is classified into three categories: direct, indirect, and idle. The basic hypothesis is that MG contributes to lowering indirect work hours and increasing direct work hours, which will eventually lead to increased productivity. In this paper, literature review about MG as well as productivity and its measurement methods are provided. In the Research Methodology section, work sampling and methods to measure time for the work sampling are presented. Section 4 presents the Expected Finding. This is followed by Future Study and Contribution in Section 5.

2. LITERATURE REVIEW

2.1. Machine Guidance

Machine guidance (MG) is relatively new in the heavy machinery-oriented earthwork engineering. MG utilizes multiple sensing and information system technologies to provide location information in real time, enabling equipment operators to work quickly with high accuracy [2].

The basic operating principle of MG is that the location-based guidance system, which is global positioning system (GPS) based, is displayed on the display board mounted on the excavator through the Digital Terrain Model with 3D design drawings with location and direction information. Through the slope sensor, the distance from the body of equipment to the end of the bucket can be determined with a trigonometric function. In addition, body inclination measurement sensor gives the information about whether the excavator is inclined (Fig.1). If an excavator cut soil for slope, the technology provides location information such as an angle of the slope. With the information, the operator can

make sure whether or not he worked to the planned level [4]. As the technology provides such information accurately, there is no need to have a surveyor who checked the angle. In addition, the operator can move to the neighborhood area for additional work without the work check by the supervisor. By saving such time with high accuracy, it contributes to not only improving efficiency and productivity, but also saving man-hours being spent for inspection. Another benefit of using MG is the precise and detailed 3D modeling of the earthwork section. Based on this, it is possible to carry out excavation work at a small cost and time, as well as to accurately predict the amount of earthwork [7]. Based on survey responses from various MG users, Vennapusa et al. (2015) reported 10 to 70% cost reduction resulting from productivity improvement according to the prediction of earthwork volume [8].

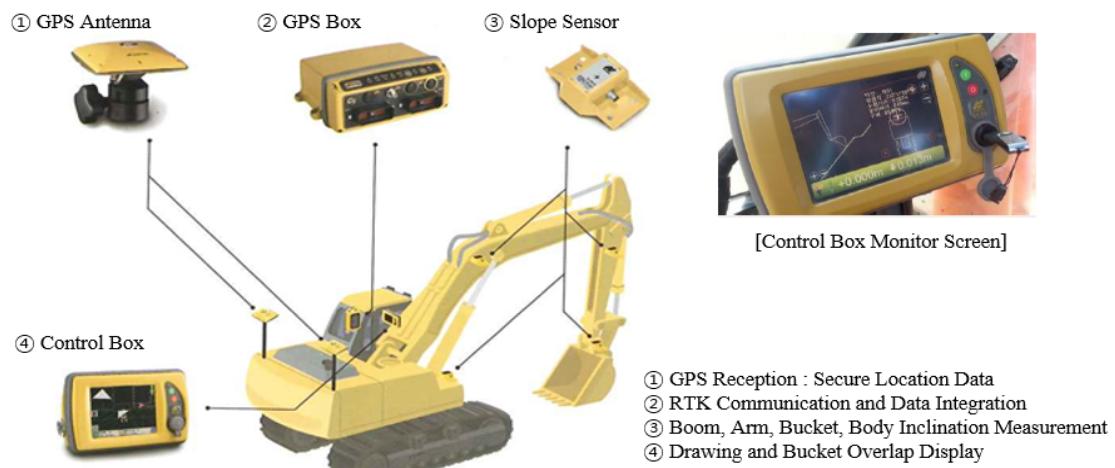


Figure 1. Machine Guidance

2.2. Construction Industry Productivity and Measurement Methods

Productivity is the ratio of input and output [9]. As there are various types of input such as cost and time in terms of labor work hours and output such as value and quantity, productivity has been defined in several ways in the construction industry. For example, the aggregate level productivity which considers the annual value created in the construction industry measured in terms of constant dollar of contracts and overall workhours of hourly workers represents the productivity in the industry level [10]. The activity-level productivity, on the other hand, focuses on the input required for an activity (i.e., workhours spent for an activity) and the output from the activity (i.e., installed quantity) [11]. One advantage of using the activity-level productivity measure is that comparisons of input and output are relatively easy as the productivity for the construction work itself is not affected by construction economic fluctuation [12]. In addition, productivity measures can be classified depending on how various input and output dimensions such as labor workhour, material quantity, and capital are taken into account. While total factor productivity combines all dimensions into one value, single factor productivity calculates the productivity by dimension separately [13]. However, these metrics have been criticized as they are often calculated after the work has been completed. If productivity is measured by these metrics, activities with low productivity are identified long after the activity is firstly implemented on site [6].

In response to this concern, work sampling can be applied to identify problems in a timelier manner as measurement of direct work hour is broadly accepted by managers for an early indicator of productivity issues [6]. Work Sampling refers to measuring the time it takes for an operator to perform activities classified into three types: direct, support, and delay [11]. Direct work hour refers to the time spent in productive work. Support work hours are time spent for management, supervision, planning,

guidance, travel time and tool movement. Delay refers to the time spent waiting for the post-process to finish, personal time and late start and early finish of work. Indeed, these terms are commonly used in other studies using the work sampling techniques with slightly different names. Chang and Yoo (2013) had two categories: effective work hour which is similar to direct work hour and ineffective work hour covering both support work hour and idle time [14]. Hwang et al. (2014) classified those as productive work hour, unproductive work hour, and idle time [15].

With these categories, various researchers analyzed how construction labors' work hours were spent in the field. Jergeas et al. (2000) found that 33%, 35%, and 32% of labors' work hours were categorized as direct work hour, indirect work hour, and idle time, respectively [13]. By measuring the work hours for masonry workers, Chang and Yoo found that 39.4% of their time was direct work hour, indicating that 23.64 minutes per hour was used productively [14]. By considering the fact that the percentage of direct work hours is consistently low from various studies, one can argue that there is a lot of room to improve productivity by increasing the direct work hour. Technologies such as MG can contribute to such improvement.

When conducting the work sampling technique to measure how work hours are spent in the field, one issue is how to measure the hours accurately. For the studies investigating construction equipment, various methodologies (e.g., image-processing, computer-vision based video interpretation model, machine learning and accelerometers etc.) have been used to measure the operation time of construction equipment. For example, hydraulic excavator's equipment idle time is estimated by using Hues, Saturations, and Values (HSV) color space [16]. Automated video interpretation model was employed to a concrete column pour operation by defining each status as waiting, idle and working [17]. Akhavian and Behzadan (2015) conducted a case study for front-end loader's activity such as engine off, idle, moving, scooping, and dumping to precisely extract activity durations by using mobile sensor and machine learning classifiers [18]. Computer vision-based algorithm for recognizing single actions such as moving, digging, hauling, swinging, and dumping of earthmoving construction equipment was presented using an algorithm which automatically learns the distributions of the spatio-temporal features and action categories [19]. As accelerometers provide a low-cost and nonintrusive monitoring system of the equipment operation, they are mounted on excavator to calculate the operational efficiency [20]. Abbasian-Hosseini et al. (2016) focused on the idle time of construction equipment as it can have the negative impact environmentally [21]. Akhavian and Behzadan (2015) used a distributed sensor network to collect data from dump truck to reduce the idle time and used discrete-event simulation to model earthmoving operation for producing measurable emission rate at the non-idle/idle rate [18]. Estimated engine speed has been used to estimated emission rates of each diesel vehicles in earthmoving activities such as idling, scooping, and dumping [22]. In summary, there are various types of technologies available to measure the work hours of construction equipment for the work sampling technique.

3. RESEARCH METHODOLOGY

3.1. Work sampling

For the work sampling in this study, we used three terms: direct work hour, indirect work hour, and idle time. As we applied the work sampling for excavation, we defined each term as shown in Table 1. Direct work hour is productive time spent for excavation work itself. Indirect work hour is time taken to support excavation activity. It includes surveying during or after excavation, grade checking to see whether the slope is excavated as planned. Lastly, idle time is time used regardless to excavation. This includes personal time of workers and late start or early finish.

Table 1. Definition of time factor

No.	Time Factor	Definition	Activities
1	Direct work hour	Productive time spent on work	Excavation
2	Indirect work hour	Time taken to perform related work	Surveying, Grade checking
3	Idle time	Time taken without regard to work	Personal time, Late start/Early finish

3.2. Measurement Method

We will compare the direct, indirect work hours for the excavators with and without MG. For the comparison, it is important to measure each time accurately. Thus, it is necessary to find a proper measurement method for time.

Videotaping is one good candidate for the time measure to conduct the work sampling. Even though it is effective and inexpensive, it takes intensive manual reviewing process and time for analysis [17]. Many other technologies have been investigated for automatic and accurate measurement of construction equipment's operation time. To find the most suitable method for work sampling technique, we will first look at several methodologies. Those methodologies can be classified into three categories as shown in Table 2.

The automatic analysis of recorded images or video uses cameras and image-processing techniques. As it is common to use cameras which produce images every 5 to 30 seconds at construction sites to monitor the construction activities nowadays, those abundant image data provide an opportunity to use an image processing approach to automatically measure idle time of construction equipment. There are several technical issues for estimating the equipment's idle time with this technology. These include the distinction between equipment and its background and determination on the equipment's status through the images. One possible solution is equipment segmentation by threshold setting approach in the HSV color space. Equipment can be tracked by using the concept of distances between objects as the location of equipment would be close in a series of images. Equipment is considered to have moved when the distance between the location of an equipment's centroid differs by more than the threshold value. The approach is known to be quite accurate. The error rate for this image processing-based method was 4.1% [16]. Another video interpretation model is investigated by Gong and Caldas (2010) [17]. This video interpretation model involves three video processing hierarchy stages. First stage uses computer vision techniques to recognize what construction objects are in the video. Second stage uses model-based computer reasoning to interpret what happens in the video. Last stage deals with using video content organization method to summarize what happened in the video. For the validation of the proposed video interpretation model, model was applied to a concrete column pour operation. Results showed average 98.85% of accuracy rate.

Besides these automatic analyses of recorded images or video, sensors can be mounted on construction equipment to diagnose its status. An accelerometer is an electromechanical device that measures acceleration. Based on acceleration data captured by small-sized, low-cost microelectromechanical (MEMS) accelerometers that are installed on equipment, operation time of construction equipment can be analyzed. Ahn et al. (2015) used the sensor to diagnose the status of construction equipment [20]. The underlying idea is that any nonstationary operating of construction equipment generates a notable level of acceleration compared to base line and any stationary operating of equipment creates distinguishable patterns of acceleration signals. By using this idea, they achieved over 93% of the accuracy with less than 2% deviation between the observed and measured in most cases [20]. Mobile sensors also can be used in the work sampling for construction equipment. Akhavian and Behzadan (2015) collected multi-modal data from various sensors (i.e. accelerometer, gyroscope, GPS, RFID) embedded in mobile devices placed inside construction equipment cabins [18]. Although the accuracy depended on the level of detail in classifying equipment's actions, the overall accuracy exceeds 80%.

Information from construction equipment itself is another source being used to diagnose the status of construction equipment for work sampling. Examples of such information include emission from

equipment and engine speed. As many local jurisdictions limit the amount of time diesel engine equipment run at idle without shutting down, construction equipment's idle time is one of the issues in the fields of environmental pollution [21]. As emission factors associated with idling is significantly different from other activities, engine speed or fuel consumption is estimated based on emission factors like concentrations of carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbons (HC), and carbon monoxide (CO) [22].

Table 2. Measurement method

No.	Type	Methodology	Author, year
1	Automatic analysis of recorded images or video	Image-processing	Zou and kim (2005) [16]
		Computer vision-based video interpretation	Gong and Caldas (2010) [17]
2	Sensor	MEMS accelerometer	Ahn et al. (2015) [20]
		Mobile sensors (i.e. accelerometer, gyroscope, GPS, RFID)	Akhavian and Behzadan (2015) [18]
3	Using information from construction equipment itself	Engine speed or fuel consumption estimated by emission concentrations	Heidari and Marr (2015) [22]

As each methodology has different characteristics, it is important to find the most suitable method for work sampling considering several factors. After selecting an appropriate method, we will compare the productivity in terms of time for excavators with and without MG when excavating same amount of soil. It is hypothesized that excavators with MG should have higher level of direct work hours. The rationale behind this hypothesis is that as MG provides information that operators want in real time, they do not need to wait for surveying or confirmation from inspectors. Thus, they can spend more time directly for excavating. By comparing the productivity improvement with or without the use of machine guidance through work sampling, we will show the improvement of productivity due to the increase in the direct work hours and decrease in the indirect work hours.

4. EXPECTED FINDING

By using the work sampling technique with selected measurement methods, utilization of operation time of excavator with and without MG will be investigated. For the measurement method selection, to pursue accuracy of measuring direct work hour, indirect work hour, and idle time, we considered to employ multiple methods among the methods in Table 2. Based on the previous studies using the work sampling technique, it is reasonable to assume that the direct work hours for the excavators without MG take at most 40% of total work hours. This indicates that more than 50% of work hours will be used for nonproductive works. Even if excluding the idle time caused by personal time or early finish and late start due to uncertainties at worksite due to weather and interference process, much of those nonproductive usage of time stems from time spent for extra surveying before and after excavation or grade checking by a surveyor. Due to these indirect activities, excavator operators should keep stopping and re-starting their works, which should hinder their productivity.

Using MG, on the other hand, should help the operators obtain every information needed during excavation in real time. In other words, MG helps to reduce indirect work hours spent for information delivery and inspection of the work. With the technology, significant portion of indirect work hours can be transferred to direct work hours, which should contribute to productivity improvement.

5. CONCLUSION

Earthwork is one important process typically being on a critical path in schedule management. However, earthwork has been carried out through traditional procedures such as surveying and stakeout. For past few decades, technology using sensing and information systems has been applied to earthwork equipment. MG is one of those technologies which provides real-time location information enabling the equipment operators to work quickly with high accuracy. MG enables to excavate without surveying before and after excavation as the technology provides topographic information to operators. It is also helpful in checking the level without surveyors throughout the operation.

As this study focuses on measuring productivity in terms of work hours on-site, work sampling is suggested for investigating of time utilization of excavator. To employ the method, it is necessary to diagnose the status of equipment and measure the time in terms of direct work hours, indirect work hours, and idle time. This study reviewed three different measurement methods using various technologies in Table 2. For the direction of future research, it is necessary to select measurement methods that best fit to our work sampling circumstances. For the selection, there should be some factors taken into account. For accuracy, it is important to establish rigid criteria for automatically matching the direct work hour, indirect work hour, and idle time. Distinguishing between indirect work hour and idle time can be a challenge for automatic measurement, as the excavator's motions related to indirect work hours and idle time should be very similar. Indeed, it is necessary to further discuss how to distinguish both in the context of the work.

Regarding the contribution of this study, while many previous studies about productivity improvement from the use of technology on construction equipment have focused on the increase of installed quantity, this study focuses on the direct work hours based on the work sampling technique. With this, this study should be able to explain why and how the productivity improvement was achieved. There have been few studies investigating why technologies contribute to productivity improvement. If this study verifies the hypothesis that equipment with MG spends has higher level of direct work hours and lower level of indirect work hours, it will help practitioners when they justify their decisions to invest in technology and design their work processes to gain higher level of productivity improvement.

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A Framework for developing the automated management system of environmental complaints in construction projects

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Abstract: Vast quantities of environmental pollutants from construction projects are causing significant damage to nearby local communities and thus generate environmental complaints. The construction company, responsible for compensating and resolving environmental complaints, suffers economic damages due to additional expenditures and schedule delays in construction projects. Meanwhile, the construction industry can stagnate from a broader perspective. Therefore, this study aimed to propose a framework for developing an automated management system which consists of two models for environmental complaints in construction projects: (i) the prediction model: a model for predicting environmental complaints based on factors related to environmental complaints; and (ii) the prevention model: a model for providing construction companies with the optimal prevention measure to effectively prevent environmental complaints according to the results of the prediction model. In addition, the algorithm for integrating the developed models into the management system in construction projects was proposed. Eventually, the application of the management system to construction projects can ensure the profitability of construction companies and mitigate damage from environmental pollutants to the nearby local community.

Key words: Automated management system, Construction project, Environmental complaint, Prediction model, Prevention model

1. INTRODUCTION

In order to complete a construction project carried out via the cooperation of various stakeholders (i.e., construction company, contractors, and residents), it is essential to maintain a good relationship between the construction company and the residents around the construction site (i.e., nearby residents) [1]. However, nearby residents who suffer from vast quantities of environmental pollutants (e.g., noise, vibration, and dust) caused by construction equipment file civil complaints with government offices to minimize the damage from environmental pollutants [2-4]. Civil complaints about environmental pollutants (i.e., environmental complaints) can be simply resolved by reducing the amount of environmental pollutants. However, if nearby residents are subject to severe and sustained damage from environmental pollutants, the construction company is forced to suspend the project or pay compensation along with legal punishment [5,6]. In other words, the construction company may not be ensured profitability from the completion of the construction project due to the economic damage

resulting from the process of resolving environmental complaints. Therefore, for the construction company to ensure profitability, it is necessary to predict and prevent environmental complaints filed by the nearby residents.

Despite the need to manage environmental complaints in construction projects, few studies were conducted regarding the management of complaints and disputes between construction companies and nearby residents. Some previous studies analyzed complaints and conflicts between construction companies (or owners) and contractors. Chou et al. [7] developed a model based on a genetic algorithm with a support vector machine that predicts whether a dispute will occur in public construction projects. Mohammadi and Birgonul [8] determined key risk factors for disputes and complaints in green construction projects based on expert interviews and surveys. Chaphalkar et al. [9] predicted the outcome of construction disputes through a neural network, and Liu et al. [10] developed a model for resolving construction disputes through a case-based reasoning approach.

In summary, several previous studies analyzed civil complaints between construction companies and contractors, but these previous studies have the following limitations. First, the subjects of civil complaints were limited to the internal groups of construction projects, and there was a lack of studies on environmental complaints filed by the external group (i.e., nearby residents). Second, previous studies developed methods to predict or resolve civil complaints, whereas studies to deal with the prediction and prevention of civil complaints at the same time was insufficient. In this regard, this study aimed to propose a framework for developing an automated management system capable of predicting and preventing environmental complaints filed due to environmental pollutants from construction projects.

2. AN AUTOMATED SYSTEM OF ENVIRONMENTAL COMPLAINTS IN CONSTRUCTION PROJECTS

This study proposed a framework for developing a system to automatically manage environmental complaints in construction projects from the perspective of construction companies (refer to Figure 1). This automated management system of environmental complaints consists of two models: (i) the prediction model; and (ii) the prevention model. The specific methods to develop the automated management system are as follows.

Development of the automated management system for environmental complaints in construction projects

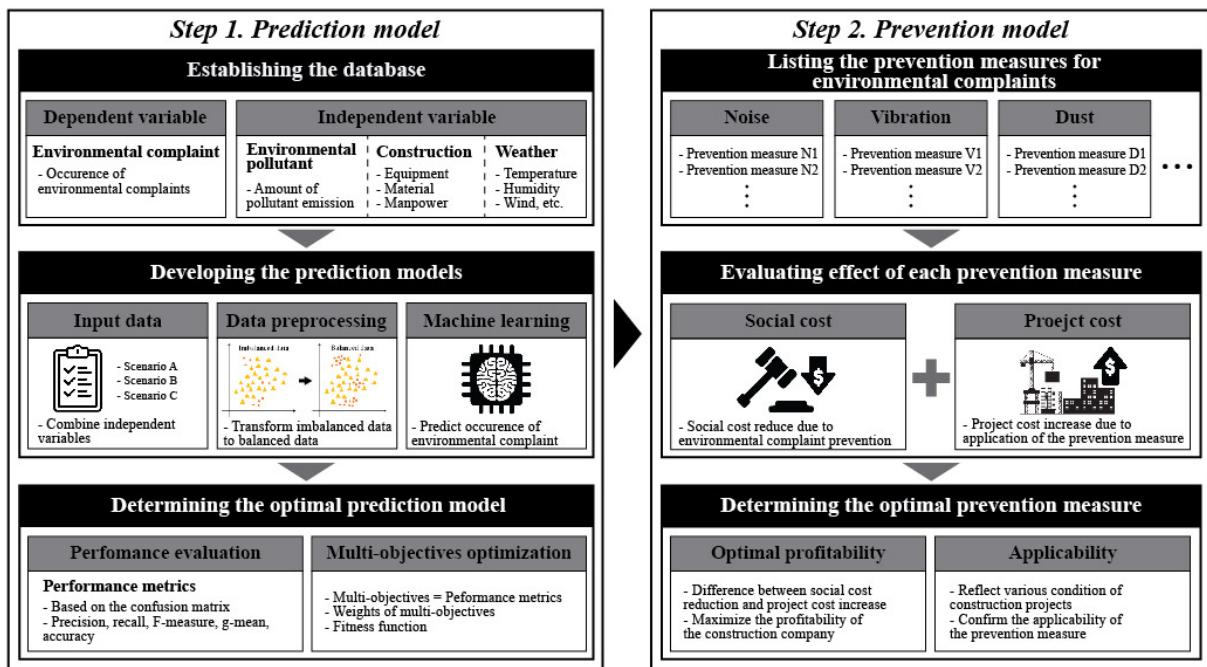


Figure 1. Research framework

2.1. Prediction model

The model that predicts the probability of occurrence of environmental complaints (i.e., prediction model) can be developed through three stages.

First, a database of the dependent variable (i.e., environmental complaint) and the independent variables (i.e., environmental pollutant, construction, and weather, etc.) should be established for prediction models to be developed. In prediction models, the dependent variables are used as the output data to be predicted, and the independent variables are used as the input data needed for the prediction. Since the number of occurrences of environmental complaints to be predicted is relatively lower than the number of non-occurrences, the established database is imbalanced.

Second, various prediction models can be developed depending on input data, data preprocessing, and machine learning. First of all, scenarios for the type and number of input data that affect the performance of the prediction model should be selected based on the collected independent variables [11]. Next, in order to develop and validate the prediction models, the database should be classified into a training set and a test set, and a k-fold stratified cross-validation that divides the proportions of minority and majority classes into a k number of subsets of equal size to effectively validate prediction models for an imbalanced database should be used [12]. In addition, since the prediction model developed based on the imbalanced training set has a limitation in that it derives biased results, a data processing method (i.e., oversampling and undersampling) should be determined to convert imbalanced data into balanced data [13,14]. Lastly, machine learning (i.e., logistic regression, support vector machine, random forest, etc.) to predict the probability that environmental complaints occur should be determined.

Third, the optimal prediction model with the best performance should be determined among the various developed prediction models. The predictive performance can be evaluated by inserting the test set into the prediction model to compare the predicted and actual values. In addition, confusion matrix-based performance metrics (i.e., precision, recall, F-measure, etc.) that can evaluate the predictive performance for imbalanced data should be used as evaluation index [15,16]. Finally, the optimal prediction model that reflects predictive performance in terms of several performance metrics should be determined using a multi-objective optimization approach [17,18].

2.2. Prevention model

The model that determines the optimal prevention measure for environmental complaints (i.e., prevention model) can be developed through three stages based on the prediction results of the developed optimal prediction model.

First, possible prevention measures should be listed by the type of environmental pollutants. The types of prevention measures and the impacts of prevention measures on the projects (e.g., amount of environmental pollutants, construction period and costs, etc.) should be listed all together.

Second, the listed prevention measures should be evaluated in two categories from economic aspects: (i) social cost; and (ii) project cost. The social cost refers to the total costs that the construction company pays compensation for environmental complaints. Changes in the expected social costs due to a decrease in the probability of occurrence of environmental complaints should be evaluated based on the application of the prevention measure (refer to Eq. (1)). The project cost refers to the total costs incurred in carrying out the construction project. Changes in the project cost due to the application of the prevention measure, including additional costs for the prevention measure, should be evaluated (refer to Eq. (2)).

$$\Delta SC = (ECP_A - ECP_B) \times ECC \quad (1)$$

$$\Delta PC = PMC + (PC_A - PC_B) \quad (1)$$

where ΔSC is the change in the social cost, ECP_A and ECP_B are the probabilities of environmental complaints after and before the application of the prevention measure, ECC is the compensation cost for the environmental complaint, ΔPC is the change in the project cost, PMC is the cost of the prevention measure, and PC_A and PC_B are the cost of the project after and before the application of the prevention measure.

Third, the optimal prevention measure should be determined from the evaluated prevention measures. First of all, the prevention measure capable of maximizing the profitability of the construction company should be selected in consideration of a decrease in social cost and an increase in project cost. Then, the applicability of prevention measures to the current construction project should be evaluated. Eventually, the prevention model should be designed to ensure the proper determination of the optimal prevention

measure that can maximize the profitability of the construction company among the prevention measures applicable to the construction project.

2.3. Integration of the prediction and prevention models

This study proposed an algorithm to integrate the prediction and prevention models into the automated management system of environmental complaints (refer to Figure 2). The details of the algorithm are as follows.

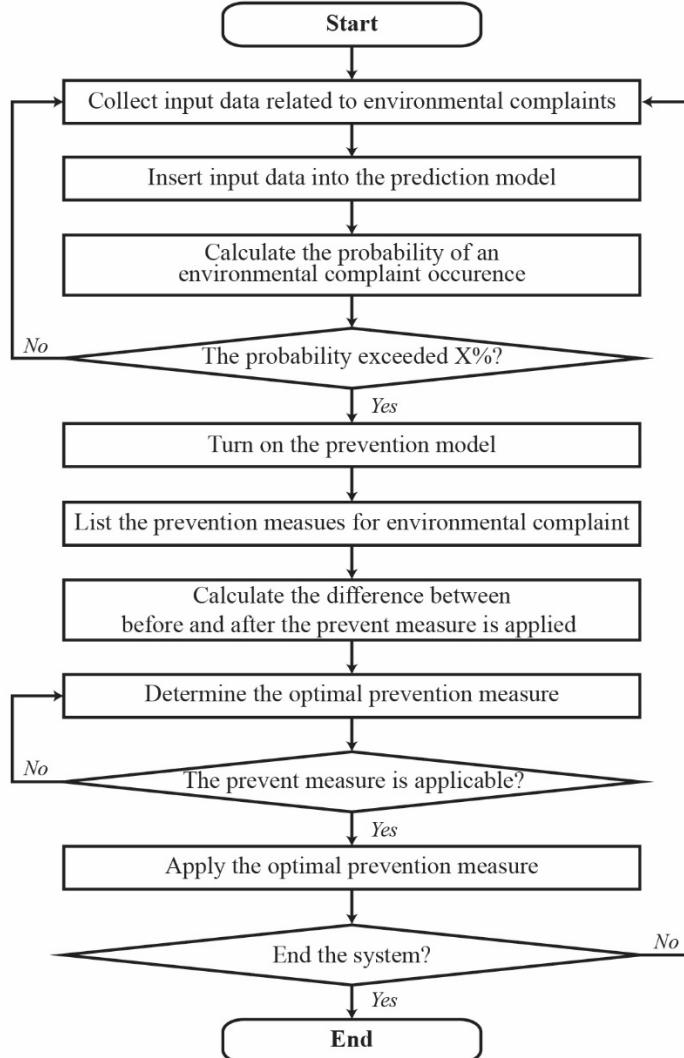


Figure 2. Integration algorithm for prediction and prevention models into the automated management system

First, the input data of the optimal prediction model should be collected using IoT-based sensor networks, cloud computing, etc.. The collected input data is automatically inserted into the prediction model, and the prediction model calculates the probability of occurrence of environmental complaints according to the input data.

Then, the prevention model works when the probability of occurrence of environmental complaints exceeds the probability X% (i.e., the minimum probability of occurrence of environmental complaints to which the prevention measure should be applied) set by the construction company in advance. In contrast, if the probability of occurrence of environmental complaints is less than X%, the prevention model does not work and returns to the first stage (i.e., data collection). When the prevention model works, all prevention measures to prevent environmental complaints are listed. Then, the decreasing social cost and increasing project cost are calculated according to the application of each measure to the construction project. Finally, the prevention model determines the optimal prevention measure of the construction company from economic aspects and evaluates the applicability of the optimal prevention measure in consideration of the current construction project conditions. If the optimal prediction measure is applicable, the construction company should apply the prevention measure to construction

projects. However, if not, the alternative prevention measure should be selected instead. After applying the optimal prevention measure to the construction project, the construction company can keep the system running or terminate its operation. Through the above procedure, the automated management system of environmental complaints can be integrated and applied to actual construction projects.

3. CONCLUSION

This study proposed a framework for developing an automated management system that can predict and prevent environmental complaints in construction projects.

As a result, the developed automated management system of environmental complaints can make contributions to the construction industry and nearby local communities. First, the system manages environmental complaints, which serve as factors that reduce the profitability of a construction company, thus ensuring the profitability of the construction company and further activating the construction industry. Second, the fact that nearby residents do not file environmental complaints means that they suffer less damage from environmental pollutants from the construction project. This, in turn, suggests that the developed management system can be used to reduce damage to nearby local communities due to environmental pollutants from construction projects.

Despite the aforementioned contributions, this study only proposed a framework without a numerical application. Therefore, for future work, detailed research on the developed framework will be carried out on a systematic basis to establish an automated management system of environmental complaints. Furthermore, based on the evaluation and improvement through the application of the automated management system to various construction projects, the research team set the generalization and popularization of the automated management system as a tool for managing environmental complaints in the construction industry as its final goal.

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**XVII. SUSTAINABILITY
CONSTRUCTION AND
MANAGEMENT III (F2)**

“Standard Model” approach to building projects in the UK and potential role of project team to mitigate any local difference~ from international developer’s perspective

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Abstract

In order to improve the sustainability and smart construction, it is discussed arguably that developing and applying consistent “standard model” to plan business, design, construct and operate a building is considered to be one of the effective and efficient approach.

The scope of this article is to examine, from the international developer’s perspective, the “standard model” approach of a hotel brand to building projects in the UK, and also to explore potential role of project team to mitigate any local difference at the project level. These projects are developed by the same developer adopting the same business plan, design and operation to each project. In order to clarify the actual and likely difference in construction results, reference is also made to those building projects located in other geographical markets including Japan, Germany and USA, and focus is given on the analysis of its programme and cost.

Principle findings are that there exists geographical difference especially in environmental and planning system, and that major local difference is found at least in the programme at the design stage. In contrast, the difference in the building cost itself may not be necessarily considered major if currency exchange rate being taken into account appropriately. It is also observed that there were cases where any difference in the programme was mitigated by taking different approach to procuring and defining roles of management and professional team at the project level.

In conclusion, from the international developer’s perspective, the geographical difference of the “construction system” surrounding building projects can typically lead to major prolongation of programme, however, these different construction results could be mitigated at least to a certain extent by introducing appropriate changes to the role of project team.

Key words: Standard model, Carbon footprint, Conservation, Wind climate, Project team

BACKGROUND, LITERATURE REVIEW and INTRODUCTION

Standard model has been discussed as one of the methods to improve the sustainability and efficiency of construction, however, the approach and number of case studies of those actual challenges and risks at the project level are limited. Therefore, there is an expectation among the developers and clients for a more practical methodology of project management to be developed. For example, Fisher¹ analysed that actual risks perceived by the office developers in the UK are largely “market risks” (such as letting and rent), whereas, Egan report² identified instead the systematic problems which lead to actual “construction risks”. RICS³, CIOB⁴ and other professional bodies have identified the problems of difference in industry practices and worked out various “standards” how professionals work professionally and ethically. However, Koskela⁵ pointed that there is a potential bigger role for the academics to play. Among others, case studies are considered to be an area to be further developed⁶, and some of the efforts are seen in several academic and professional journals and conferences.^{7,8,9,10}

The objective of this paper is to examine the standard of an international hotel brand to clarify both business and design & construction model, to study the risks of those models in terms of carbon emission, conservation and wind climate within the UK context, then, to measure the impact on the project programme and cost, and to assess the role of project team to mitigate those risks. The measure and methodology of the research is to choose an actual case of a development project in the UK in which the author himself has been involved, to identify the risks, and to suggest possible solutions based on quantitative assessment. Key findings are that risks for a standard model can be seen in environment and planning system such as carbon emissions, conservation and wind climate mainly due to different regulations, and those risks can affect the programme if not cost of the project. One insight from this research is that international developers are taking different management strategy against these risks, however, there is a possibility that appointing a local professional ‘deputy’ could be one of the effective management options.

1. SUSTAINABILITY and SMART CONSTRUCTION

The problems of project management have been approached largely from three aspect which are to increase the value, reduce the cost and make ease of comparison & compatibility. Those issues around sustainability and smart construction can be approached in the same way, however, in this article, focus is placed on the standard model how it should be developed and applied, based on the analysis of actual projects in the UK, invested, developed and operated by international developers especially in the hotel sector.

1.1 Standard model- Business model

In the hotel sector, each brand has its own brand policy which can be applied to building production cycle of acquisition, concept, design, construction and operation. This brand policy can be a written manual which typically binds all the professionals and construction companies, such as acquisition agent, architect, engineer, contractor as well as operators, and those documents for construction tendering purpose form a part of “employer’s requirements, which have the priority over other tender documents including contract, drawing, specification, programme and cost. The extent and depth of brand policy is often detailed to the extent that it is applied to all its brand hotels regardless of difference in geographical location, building, and management team, and even customers. One example of international hotel groups shows that there are many structures and layers how the standard model can be categorized and analysed.

Table 1 –Standard business model

Category	Examples consisting standard model
1 Ownership	Founders, shareholders and directors are taking leadership and engaged in daily business
2 Partnership	Working with local land owners on long term basis, committed to local council, neighbours for sharing benefits
3 Location	Strong local presence, diversifying globally, focusing on traffic hub with regional development opportunity
4 Customer	Corporate, business and tourism customers, either domestic or international, single or family
5 Pricing	Non-fluctuating flat pricing regardless of season and location, web & membership-based booking system
6 Concept	Guest room-focused design and services, with minimum amenity facilities such as meeting room and restaurant
7 Design	Layout to maximise guest room numbers, standardised guest room and common facility, off-site manufacturing
8 Construction	Internal design, construction and maintenance team. Separate construction sequence for Shell&Core, Fit-out, FFE
9 Services	Wide variety of services including breakfast, laundry, business counter, night gowns, slippers and cosmetics
10 Management	Branch manager-focused recruitment and management supported by central procurement system

Firstly, the scope of standard model is not limited only to design or construction rather it covers all the process of building production cycle. Secondly, the level of standard model can be as detailed as seen in the guest room dimensions. Thirdly, the consistency of standard model is observed as is seen in Japan where most of the hotel branches have same building design including external façade and internal fit out details. Overall the business model as well as operation model are observed to dictate the physical features of the building including location, size, layout and even the external and internal design of both architecture, structural, M&E and other engineering. Interestingly, however, large difference in external façade can be seen in the buildings in France and UK compared to those in Germany, US and Japan. One of the reasons for this is considered to be that the local authority in France or UK has more discretionary power in terms of development and building permit especially around the design of external façade of the buildings , whereas the rules and principles in Germany, US and Japan are considered more prescriptive and written in the laws, codes and regulations. In contrast, the difference in architectural internal layout is considered minor, although some difference related with fire or acoustic regulations (e.g. door width, corridor width, staircase, smoke ventilation, fire hydrant, insulation) is still observed. Further, mechanical and electrical design has wide diversity especially around the energy resource and heating equipment, for example, where the brand policy is to provide electric hot water equipment to each guest room, to which the UK currently imposes tighter CO₂ conversion rate of grid electricity whereas US and Japan have less or almost no compulsory regulations in this area. There was no significant difference in terms of ventilation, air conditioning, water supply or foul or rain water system, although the location of air conditioning condensers is found different (e.g. balcony, each floor, roof, or others) depending on the regulation of external façade as well as the height of the building.

1.2 Standard model approach- Design & Construction model

When the business is considered to be standard model regardless of its geographical location, a question arises whether the building design and construction can or should also be standardised in a particular country or jurisdiction, if so, whether that would contribute to the overall concept of sustainability and smart construction. In particular, the issue for a hotel brand which has coherent standard model spanning from business model, building design, construction and operation, is whether he should pursue its building design standard model in a country where there is wide difference in terms of climate, regulation, building production system and people. In this chapter, a more detailed analysis has been conducted in terms of the physical features of building especially the layout of the buildings. This is because the value of the buildings for this model can be and is calculated simply based on the number of the guest rooms, as the room price for guest rooms does not fluctuate depending on the seasons or booking status(busy or empty occupancy) and it is also almost flat (except for the difference in exchange rate) as the absolute figures compared to other branches of this brand in different global locations (e.g. 60 UK Pound, 60 Euro, 60 US\$, 6,000 JPN Yen). Further, there are no income producing facilities with the building other than guest rooms as there are no restaurants, meeting rooms, spas and any other space of amenity or ancillary function, which means that maximizing the number of guest rooms is the highest priority at least for building design (taking into account of course of the effective and efficient construction and operation at later stages).

Table 2: Design & Construction model (Source: UK Planning Portal)



Based on this principle to maximise the number of guest rooms and efficiency rate of the floor area, a study has been conducted on a building of total floor area (GIA) of 7,400m², typical floor area (GIA)

of 322m² and 23stories high (with no basement). This is essentially to define the minimum size of the guest room and to maintain the minimum width of corridor based on the I shape layout as above. In this model, the width of guest room is 2.85m dictated by the width of guest room door(1.0m) and unit-bath pod (1.7m), and length is either 4.5m (single room), 5.0m (double room) or 5.5 m (twin room) dictated by the width of bed (1.6m), desk (0.45m), chair (0.75m) and unit-bath pod (1.5m), likewise the floor to floor height is 2.85m dictated by the height of unit-bath pod and minimum clearance above the unit-bath pod for supply & drainage pipes, ventilation and electric heater. From structure aspect, this will create a concrete shear wall and flat slab (200mm thk) system, with one staircase for fire escape route maintaining minimum escape route length, with minimum one lift for firefighting lift together with smoke ventilation and fire hydrant system incorporated within the lift lobby, coupled with one or two more passenger lifts. From acoustic perspective, internal partition walls are either concrete shear walls of 175 mm or metal stud and double plaster boards of total 150mm thick with thermal and sound insulation, floor is concrete with steel trowel finish covered by tile carpets, and wall is covered by the cloth or paint, ceiling is suspended and covered by plaster boards with cloth or paint finish. Overall, this would create a floor plate of 26.5 m length and 12.5 m width, maintaining maximum fire escape length of 15.0m. Total floor area is appx 330.0m², including total floor area of guest rooms of 250.0m², efficiency rate is 75.0% at a typical floor. Mechanical and Electrical equipment are installed for each guest room including unit-bath pod, ventilation, air conditioning, electric heater for hot water, so that it is risk-free or risk-less even in the face of natural disasters which might cause damages to the central system requiring all the guest rooms to be closed as not functioning in satisfaction.

2. STANDARD MODEL and ITS CHALLENGES

When implementing standard model, environment and planning system in each country creates another challenge mainly because each project is required to submit detailed planning application to the relevant local authority for approval, although it is rare for the environmental impact assessment to be required for a typical small to medium size building project in the city environment. This is typically the case in the UK where there are less prescriptive regulations around the planning and building regulations for example about the building usage, mass and height, which places almost all international developers in a difficult situation as the bases of assessment are literally the subjective view of the authority.

2.1 Carbon footprint

Providing an individual electric heater with 23kw capacity (for bath and wash basin hot water) for each guest room is the standard brand policy. However, under National Calculation Methodology (NCM) modelling guide (for buildings other than dwellings in England and Wales) which is a model to calculate the CO₂ emission for a nominal building, grid supply electricity is treated as Class D fuel oil. This means that CO₂ calculation of electric heater system is much higher than gas boiler system, thus it is often the case that gas boiler system becomes the only option to achieve the reduced CO₂ emission target as a condition of planning permit unless biomass and other LZC system can be adopted (which is almost impossible within city environment due to lack of supply of those renewable energy sources) . It is expected, however, that review of the CO₂ emission of grid supply electricity may be confirmed in 2020 which then reduces the value down to 250 gCO₂ eqkWh (similar level to gas boilers) from the current max 550 gCO₂ eqkWh. The expectation is that CO₂ consumption of grid supply electricity will further fall to 100gCO₂ eqkWh in 2030, however, this example shows how the regulatory system is uncertain, which makes the implementation of standard approach almost impossible in some cases.

Table 3- Carbon footprint estimates for water heating, Carbon footprint estimates for electric heating technologies (Source: UK Houses of Parliament postnote May2016)

Technology	Footprint range (gCO ₂ eqkWh)	Number of estimates
Oil boilers	310-550	3
Gas boilers	210-380	6
Gas micro-CHP	220-300 ²²	4
GAHP	150-200 ⁴⁰	4
Bio-sourced gases	20-100 ⁴¹	2
Biomass boilers	5-200 (most below 100) ⁴²	9
Geothermal	10	1
Solar thermal	10-35	6

Technology	Electricity footprint estimate	Footprint range (gCO ₂ eqkWh)	Number of estimates
Electric heaters	Current (370)	-370	Personal Communication ⁵⁹
	Reduced (250)	-250	
	Low (100)	~100	
Ground source heat pumps	Current (370)	70-190	15
	Reduced (250)	50-125	
	Low (100)	20-50	
Air source heat pumps	Current (370)	90-250	11
	Reduced (250)	60-170	
	Low (100)	30-70	

2.2 Conservation

Conservation is one of other challenges which international developers are facing as the level of conservation is largely left to the interpretation and judgement by authority where it is practically impossible to make a good argument based on regulations and even logics. This can be seen in this case where two planning applications have been made in different years for exactly the same building design, which nevertheless led to different conclusion of the permit because of the change of views by conservation officers of the same city council. In this case, the previous property owner has obtained a planning permit in 2013 to build a new 21 stories tower and to renovate the existing building into a hotel, however, he decided not to develop the project and then sold the property to the current owner in 2014. The current owner explored the opportunity to redesign a much taller building of 32 stories however were not able to gain even preliminary consent of the council and the original planning permitting has expired in 2017(after 3 years validity period). Eventually, the developer was required to go back to the original design of same height for resubmission. However, that second application was not straight approved because the authority increased the level of conservation of the existing building. As a result, significant amendment of design was needed prior to gaining 2nd approval in 2019. TCPA (Town and Country Planning Act1990, clause 54(a) (repealed by Planning and Compulsory Purchase Act 2004) says that “If regard is to be had to the development plan for the purpose of any determination to be made under the planning Acts the determination must be made in accordance with the plan unless material considerations indicate otherwise.” This clause is considered to allow the authority to make their own judgement different from the local plan if material considerations indicate otherwise, as such, some aspects (e.g. conservation) are often treated to be more important than commercial viability of the project, which could lead to a conflict between the conservation and development, unless those are well balanced considering both short-term and long - term merit for the developer, users, neighbours, city councils and other wide stakeholders.

2.3 Wind climate

New challenges within the city environment can also be found around the wind climate as a result of taller and high-density building environment where typical down drafts between buildings cause uncomfortable and dangerous conditions around the neighbouring buildings and streets. This among others will demand standard model approach to subject itself to mediations such as reviews of building direction, height as well as additional canopy and other protection around the entrance and ground floor level. The problem observed is, however, not only the increased demand and sensitivity around the wind climate but also the fact that approach and method of assessing wind climate is not clear as it is expected, and it is often that different approach is used against unreliable data which lead different experts in this area into different conclusions and mitigation advice. As an example, one expert carried out the desk top study and confirmed the requirement of 3m width canopy over the surrounding entire pedestrian pavements, whereas another expert recommended wind test which concluded there is no problems of wind climate even post to the completion of the newly proposed development. In these assessments, however, the question may lie around the interpretation by the expert as well as by the authority who ultimately is required to make decision in terms of acceptability of the wind climate report where it is difficult to identity clear regulations or guidance established in this area.

Table 4- Wind tunnel test and its result (Source: microclimate)

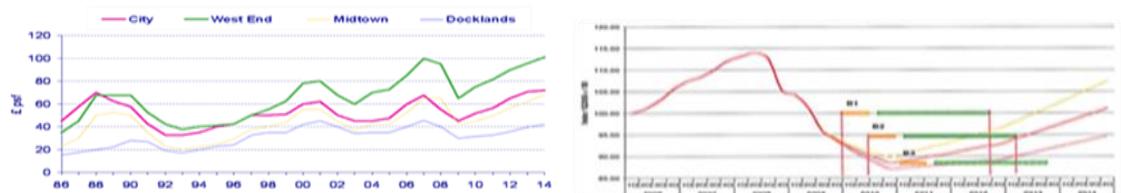


3. IMPACT ON PROGRAMME, COST and PROJECT TEAM

The impact on programme can be analysed from these two aspects, which are standard approach and sustainability challenges. Under the business plan, if the developed building is to be leased to a third party operator, additional risk of programme and cost arise mainly because the lease price fluctuates during the development stage until the developer agrees the lease price with the operator, and third party operation has his own brand policy which needs to be taken into account for design and construction.

This becomes more complicated if the developer owns the leasehold title of the land and not the freehold title, because the leasehold title has the lease period beyond which the rights to the land (and property) will be lost and also the freeholder has a power to intervene in the development and future operation by way of development agreement, license agreement and so forth, which would increase the risk of programme and cost. In this case we examined in this article, however, the business plan for the developer is to acquire the freehold title and to operate the building by itself post to construction completion, therefore no risks associated with these have been observed although the developer shall be left to the direct risk around the future income as that is affected by the room price and occupancy rate and operation cost in the future. As background, this is considered to reflect both economic and social changes since Law of Property Act 1925 where the land ownership and usage are separated in principle, allowing flexibility to the land and stake holders to improve the value, programme and cost.

Table 5 - Rent income in each district in London, Construction cost and forecast- financial crises
 (Source: K. Tanaka, case study for RICS Assessment. CBRE and Davis Langdon)



3.1. Programme analysis

Once the project team is set up, it takes two years to obtain planning permit and commence construction (1 year for planning permit, and further 1 year for preparation for construction), whereas the construction takes only 2 years. This is further exacerbated by the risk and fact that the developer may not even be able to obtain planning approval if their approach was not acceptable for the authority, and that obtained approval places conditions to gain further approval of external cladding mockups and other minor amendments. Contrary, planning permit in Japan (Germany and US) is either not required or prescriptive, and building permit is also prescriptive in these countries, which takes in Japan only 9 months (3 months for each design, permission and preparation for construction). Lastly, there is no major difference observed in the construction programme.

Table 6– Building development Programme

3.2. Cost analysis

UK development and design cost are high due to requirement to resolve property rights associated with the neighbours (e.g. rights of light) and heavy involvement in planning process. The statutory fixed fee for architects in Germany is higher, whereas it is less in US and Japan, especially because contractors

in Japan (typical D&B contractors) tend to play a bigger role in terms of development and design. In terms of building cost, construction room size is appx 15.3m², and efficiency rate is appx 0.62, which leads to estimated cost per room of appx £60,000. We do not yet have data of actual construction cost in other countries, however, based on the assumed market construction cost, the building cost is expected to be between US\$ 55,400-72,700 per room in these countries.

Table 7 – Calculation of cost per room

Calculation of cost per room		UK		Japan		Euro		US	
Assumed Market Construction cost		225	£/sf	1,000,000	JPN/Tsubo	2,250	Euro/m ²	2,250	US\$/m ²
Local Cost per m ²		2,419	£/m ²	303,030	JPN/m ²	2,250	Euro/m ²	2,250	US\$/m ²
Exchange rate(actual)		1.193		0.009		1.083		1.000	
US\$ Cost per m ²		2,952	US\$/m ²	2,755	US\$/m ²	2,414	US\$/m ²	2,250	US\$/m ²
Assumed Cost per room		59,625	£/room	57,448	£/room	50,333	£/room	46,921	£/room
Room size(actual)		15.28		7,751,301	JPN/room	7,468,231	JPN/room	6,543,290	JPN/room
Efficiency rate(actual)		0.62		65,689	Euro/room	63,290	Euro/room	55,452	Euro/room
		72,743	US\$/room	67,893	US\$/room	59,484	US\$/room	55,452	US\$/room

3.3. Role of project team

There is wide difference between the international developers in terms of their own experience and knowledge both in their sectors and local area. In this analysis, experience and knowledge are categorized into 3 layers of level 1 fundamentals, level 2 demand & supply, and level 3 standards and professionals. Among 5 Japanese developers, 2 Japanese professional developers have level 1&2 experience and knowledge whereas 2 other non-professional Japanese developers do not have in any layer. In contrast, among 5 Asia developers (Singapore, Malaysia, China-HK, China, Taiwan), 4 professional developers have experience and knowledge in 1&2 layers whereas one non- professional developer does not have experience and knowledge in any layer. None of Japanese nor Asia developers have the depth of experience and knowledge in the level 3 layer which is Standard and Professionals.

Table 8 - Developer's experience and knowledge: ○=Yes, ×=No

Japanese Developer experience&knowledge	A	B	C	D	E	Asia Developer experience&knowledge	F	G	H	I	J
Level 1: Fundamentals	○	○	○	x	x	Level 1: Fundamentals	○	○	○	○	×
Level 2: Demand & Supply	○	△	x	x	x	Level 2: Demand & Supply	○	△	○	○	×
Level 3: Standards & Professionals	x	x	x	x	x	Level 3: Standards & Professionals	x	x	x	x	x

Among 5 Japanese developers, 4 had their management present in the UK, and one did not have any management present in the UK. 3 professional developers appointed PM either internal or external, or equity partner (or both). One of non-professional developers appointed PM, and the other did not because it appointed contractors directly. Among 5 Asia developers, all 5 developers appointed PM either internal or external (or both). Among 5 Japanese developers, A and C managed successfully, B, D and E failed. Among 5 Asia developers, F, G, I and J managed successfully, and H failed.

Table 9 - Developer's contract arrangement of “deputy”: ○=appointed, ×=not appointed

Japanese Developer	A	B	C	D	E	Asia Developer	F	G	H	I	J
UK Management	○	○	x	○	○	UK Management	○	○	x	○	○
internal PM	○	○	○	x	x	internal PM	○	○	x	○	×
external PM	x	○	x	○	×	external PM	○	x	△	x	○
equity partner	○	x	x	x	x	equity partner	x	x	x	x	x
Assessment	○	x	○	x	x	Assessment	○	○	x	△	○

Table 10 – Developer's contract arrangement of “professional”: ○=appointed, ×=not appointed

Local Project team	Director	Manager	Architects	Engineer	QS	Workers	Maintenance
Full employment base	○	○	○	○	○	○	○
Mix- Station and Outsource	△	△	△	△	Outsource	Outsource	Outsource
Outsource base	△	○	Outsource	Outsource	Outsource	Outsource	Outsource

There are wide variations observed in terms of the nature of developers, policy of developers, as well as the management of developers. Firstly, there is indication that all developers are willing to establish their status within the local area by appointing “deputy”. Secondly, the measures to appoint a “deputy” are diversified, either setting up local subsidiary company, equity partnering with local companies, dispatching an expat director, employ a local manager, or outsource to external professionals. Meanwhile, there is also a tendency that most of new coming developers struggle to establish the right management style, although existing developers seem to have already established their own management style which are however very different between developers. Among existing developers, it is also observed that their management style has changed over the years depending on locations and circumstances. One case is full employment of almost all types of professions and jobs, the other is almost full outsource, although there existed a case of mixture of these two extremes.

CONCLUSION

Issues surrounding sustainability and smart construction are analysed from the aspect of standard model in the hotel sector. The extent of standard is wide covering both “soft” business model and “hard” building model, however, it is observed that there exists a standard model in the market, which is described as brand policy or employer’s requirement, occupying important position among and against concept, design, construction and operational documents and procedures. However, implementation of standard model often faces challenges especially from environment and planning system. Detail analysis of carbon footprint, conservation and wind climate is conducted and impact on programme, cost and project team are measured and discussed. In summary, from the international developer’s perspective, it can be said that the geographical difference of the “construction system” surrounding building projects can typically lead to major prolongation of programme if not cost, however, these different construction results could be mitigated at least to a certain extent by introducing appropriate changes to the role of project team, especially at least by appointing a professional “deputy” for a building project.

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Influencing Variables and Keywords of Technology Strategy for Modernized Hanok Research

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Abstract: As eco-friendly and sustainable architecture is becoming more popular, the interest in Korean traditional wooden buildings (Hanok) has also been increasing. The building technologies of the wooden construction have been actively developed in all over the world through the diversification of new materials and construction methods. On the other hand, the growth rate of wooden construction market is still slow in Korea. In an attempt to promote the Korean traditional wooden buildings, a comprehensive research project has been conducted. This R&D project is developing standard designs, new materials, and methods for modernized Hanok including houses, public buildings, long-span structures, and even high-rise buildings. To this end, the purpose of this study is to formulate a technological strategy for popularization of modernized Hanok. Influencing variables and issues are analyzed and defined first. At the same time, the five keywords have examined in the perspective of dissemination of modernized Hanok technology. Finally, a technology road map for strategic development of modernized Hanok is proposed through causal diagrams.

Key words: Hanok, modernized hanok, influencing variables, keywords of technology strategy

1. INTRODUCTION

As eco-friendly and sustainable architecture is becoming more popular, the effort to develop Korean traditional wooden buildings (Hanok) has also been increasing in Korea. However, while the wooden construction market has been increasing along with the development of wooden building technology globally, the growth rate of domestic wooden construction market is still slow. As a part of effort to improve this problems, the government has been conducting a comprehensive research project on the development of modernized Hanok building technology [1]. At the same time, the issues related to technology development have examined in the perspective of dissemination and popularization of modernized Hanok technology.

The purpose of this study is to propose a technological roadmap that is essential for long-term technological development in the perspective of industry level. The research methodology is to analyze and define the influencing variables and keywords of modernized Hanok technology.

Finally, based on these analysis, this research analyzes the fundamental technical support methods and suggests a strategic direction.

2. MODERNIZED HANOK

2.1. Characteristics of Hanok

The development of Korean traditional wooden building technology has continued reflecting both the values of tradition and characteristics of contemporary life. However, there are some obstacles such as the technical difficulty, higher construction cost compared with other countries' wooden building and low residential performance, etc. [2]. Therefore, it makes it difficult to popularization the Hanok building and its technology.

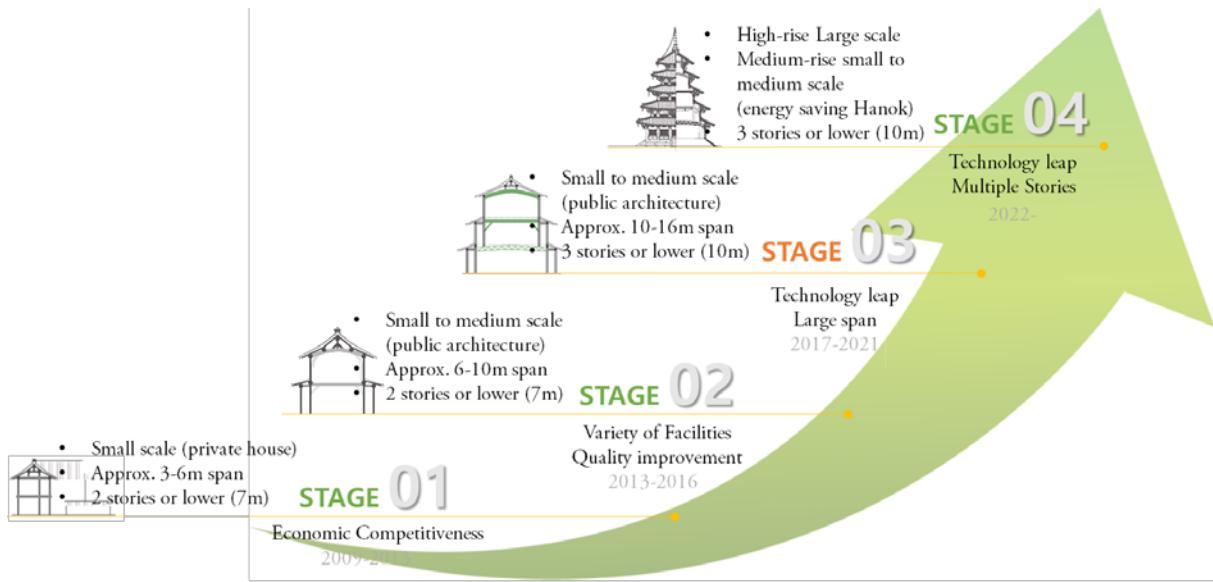


Figure 1. Long term plan for development of modernized Hanok technology [3]

Therefore, the government has been conducting a research on the advancement of modernized Hanok technology to settle these difficulties and improve economic efficiency through the development of new materials and building methods [1].

2.2. R&D project

The research on the “Development of modernized Hanok technology” has been conducted in four stages since 2010 (Figure 1). It includes a wide range of size, height and facility (e.g. from small-scale to large-scale, from low-rise to high-rise and from house to public building). This R&D project also includes the dissemination policy, architectural design, new material, building methods, construction management and information management system.

Especially, this study has focused on the reduction of construction cost and improvement of construction productivity. In addition, the applicability has been examined through six test-bed projects [2].

3. DEFINITION AND ANALYSIS OF INFLUENCING VARIABLES

In this chapter, the influencing variables of modernized Hanok technology are defined and analyzed (Figure 2). In addition, major issues are proposed for dissemination of modernized Hanok technology. Influencing variables includes timber frame type, architectural style, facility type, building size.

3.1. Timber frame type

Timber frame type is a major variable because these are related to the member size, distribution method and building methods. It can be classified into three types: light-frame wooden structure, heavy-frame wooden structure and cross-laminated timber (CLT).

Traditional Hanok has been developed into heavy-frame wooden structure with traditional and unique wood-frame method. Thus, it was limited to specific areas of building methods, design and facilities.

However, as the facilities type is diversified and the size of building is larger, to realize this, diversification of timber frame type and building methods for wooden structure is necessary. In addition, in terms of constructability and economic efficiency, it is necessary to expand the application of CLT and other wooden structures in future.

3.2. Architectural style

The architectural style can be classified by the period, materials, and structural type, etc. In this study, based on these criterions, it is categorized into three types: traditional Hanok, modern Hanok and Modernized Hanok.

Although the components of traditional Hanok have unique aesthetic aspects, complicated timber processing and joint method have been obstacles to the dissemination of Hanok to public due to technical difficulty and construction productivity.

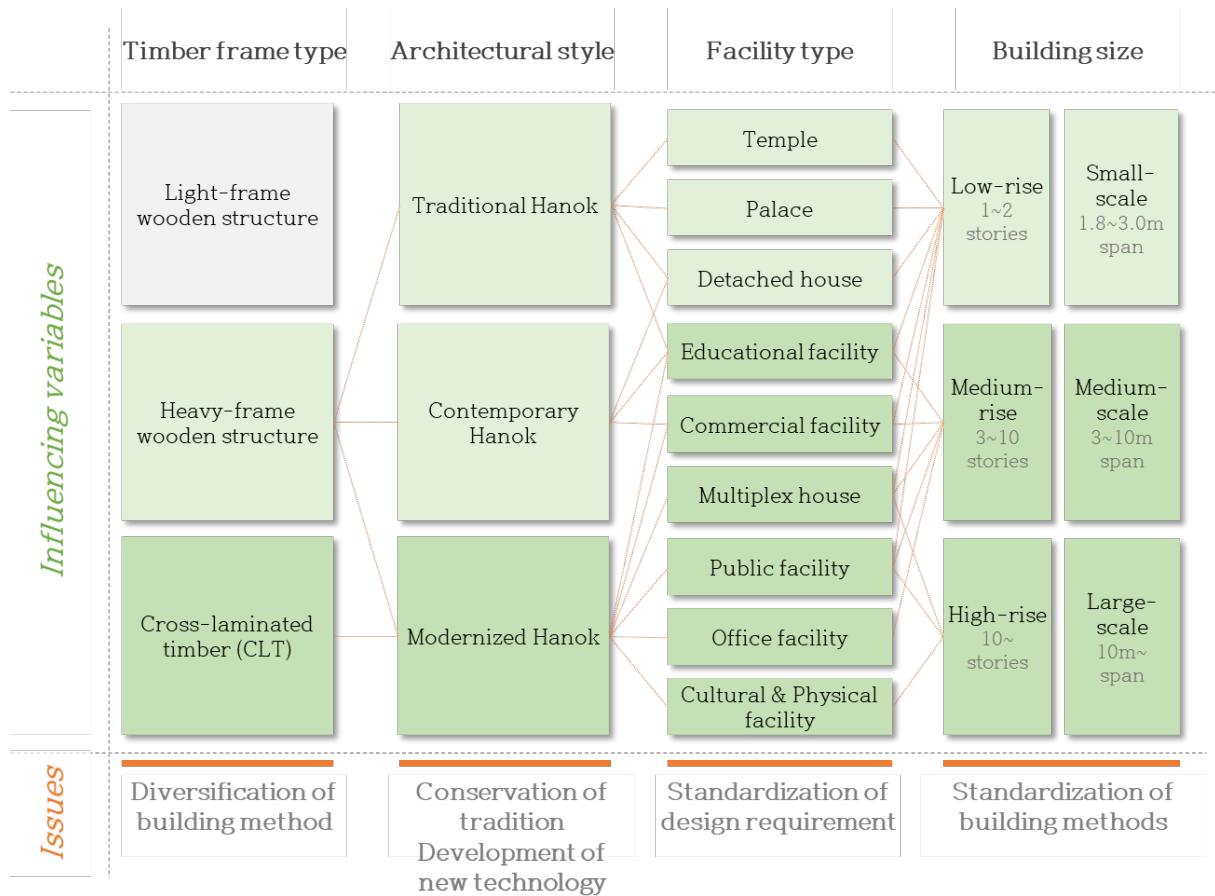


Figure 2. Influencing variables and Issues of modernized Hanok technology

In the research of modernized Hanok, various structural methods have also been attempted by changing the roof frame structure and use the joint metal instead of the traditional joint method (mortise and tenon joint). However, these alterations have been discussed as to how much can be included in the value of the tradition of Hanok. Therefore, the specific standards should be examined in terms of the conservation of tradition and application of new technology.

3.3. Facility type

Facility types are categorized according to building use and building law and consist of detached house, multiplex house, commercial and public facilities. Although the scope of traditional Hanok facility was limited to small residence, it has gradually been being expanded to multiplex house or public facilities since the modernized Hanok technology was developed.

In addition, the classification of these facilities was closely related to the building law in regards to the design standards, facilities and safety. Furthermore, it can serve as a major practical requirement for design work of the modernized Hanok.

Therefore, it is necessary to define the design requirements for each facilities and the standardization of design should be developed.

3.4. Building size

As the size of buildings becomes more diverse according to the facilities, the structure and wooden construction technology for high-rise and large-scale are required. The building size classification of Hanok is divided into low-rise, medium-rise and high-rise according to its height of the building and small-scale, medium-scale and large-scale according to the length of the beam.

Currently, there are technical difficulties to build a large-scale Hanok, so research on various structural technologies, building methods and also its application are required. In addition, the standard specifications that propose detailed descriptions of new building methods should be established and disseminated.

4. KEYWORDS OF TECHNOLOGY STRATEGY

Based on the influencing variables, the keywords of technology strategy for development and popularization of modernized Hanok were proposed (Figure 3). These five keywords include ‘standard supply chain protocols, prefabrication & OSC, industry standard classification, knowledge repository & standard performance, automated life-cycle’.

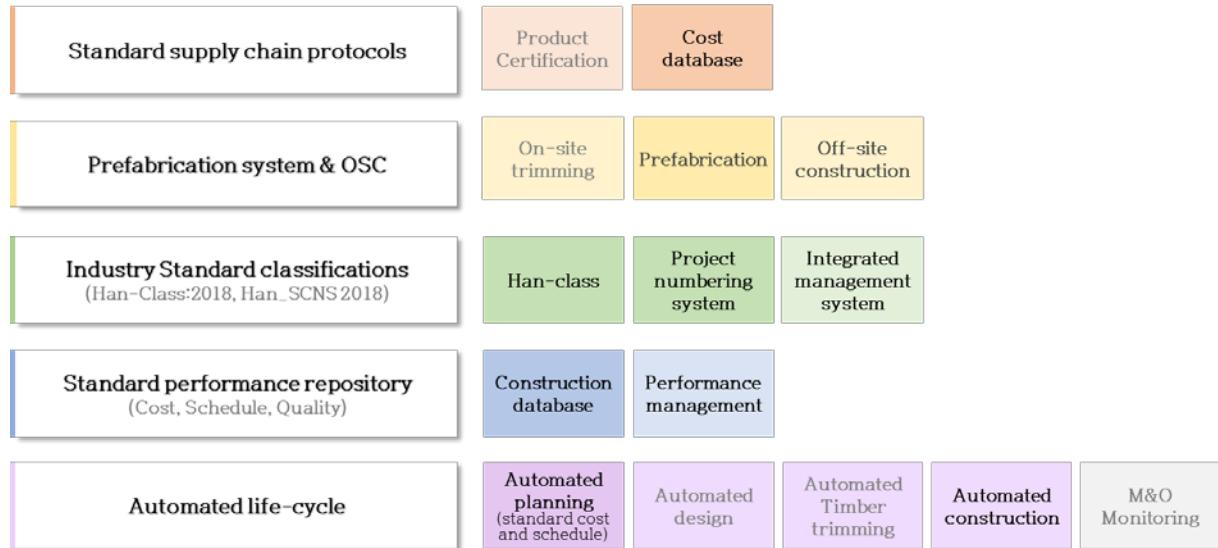


Figure 3. Keywords of technology strategy

4.1. Standard supply chain protocols

The production of standardized components and supply chain are very important in mass production and industrialization. However, the standard size and standard performance of materials used in modernized Hanok have not yet been established and the supply chain has not been organized systematically.

Therefore, there has been a continuous discussion in this study for standardization of the member size, certification of materials and establishment of efficient supply chain system. As first step to establish the supply chain for efficient procurement, the web-based construction cost catalog was developed to provide price information to general users. Also, the ways to be integrated and managed together with the standard of estimate for modernized Hanok construction was examined in the previous study.

Based on these efforts, if the historical database is accumulated more, it will be able to secure a supply chain systematically.

4.2. Prefabrication & OSC

The production method of components is a key factor that has a great influence on labor cost, time, quality, etc. Traditional Hanok applied a method of trimming timber on construction site because of its mortise and tenon joint method. However, most of the projects have currently applied the manufacturing method, and it has also been converted to prefabrication method and modularization [4]. In particular, in order to reduce labor cost, which is a big part of the Hanok construction project, the pre-fabrication should be applied actively. Furthermore, if the standard of materials and supply chain system are well established, the off-site construction (OSC) system will can be systematically applied to shorten the construction time, improve productivity and quality of Hanok.

4.3. Industry standard classification

The establishment of standard provides efficient measures for practical implementation at the industrial level and builds the base of industrialization system. It is also the most basic thing in order to share the information of each project participant. In this study, the classification reflecting the characteristics of Hanok (HanClass: 2018) was developed, and it has been continuously updated in order to be used to any modernized Hanok construction project.

In addition, based on these standard classifications, project numbering systems (PNS: work breakdown structure, cost breakdown structure, physical breakdown structure, geometry breakdown structure, etc.) was developed for automated data collection and analysis.

It also provides standard statement and schedule which can be universally available for all Hanok projects. Furthermore, the 5D-CAD integrated management system developed based on geometry breakdown structure (GBS) facilitate efficiency for project management. In order to continue the integrated data management for automation of project management, it is necessary to continuously develop and update these standard [5].

4.4. Knowledge repository & Standard performance

The actual construction data in the relational database based on HanClass (2018) enables to manage project schedule, cost and performance and also it is actively used for research through the automated analysis. For example, the previous researches include the following subjects: the productivity analysis by work section of modernized Hanok according to changes in building methods and materials [6], cost and duration analysis according to development of building method [7] and influencing factor of variation of building method and cost [8].

In addition, the guideline can be suggested based on construction database, which can lead to systematic performance management with 5D-CAD.

4.5. Automated life-cycle

The research on the automation in entire throughout the project life-cycle has been performed to improve productivity and reduce cost. In the planning phase, an automated program was developed to make a standard statement and an initial schedule easily depending on the project information. Also, in the design phase, the BIM library, algorithm [9], and the structural design software [10] was developed to provide the general public with design tools that help them to design Hanok more easily.

In construction phase, a rafter machining process was invented that could easily produce members of Hanok using laser scanning technology to reduce the labor costs [11]. In addition, a preliminary study on mobile application using augmented reality technology and 5D-CAD was conducted for improvement of workability and schedule management on Hanok construction site. Likewise, the construction robot manipulator for automation on the construction site should be introduced more actively to reduce the cost of the Hanok project. These studies have identified the possibility of comprehensive management throughout the life-cycle based on a 5D-CAD system. In addition, if automation in the M&O phase are further studied, it is expected that integrated project management in the entire life cycle will be possible in the future.

5. CASUAL DIAGRAM

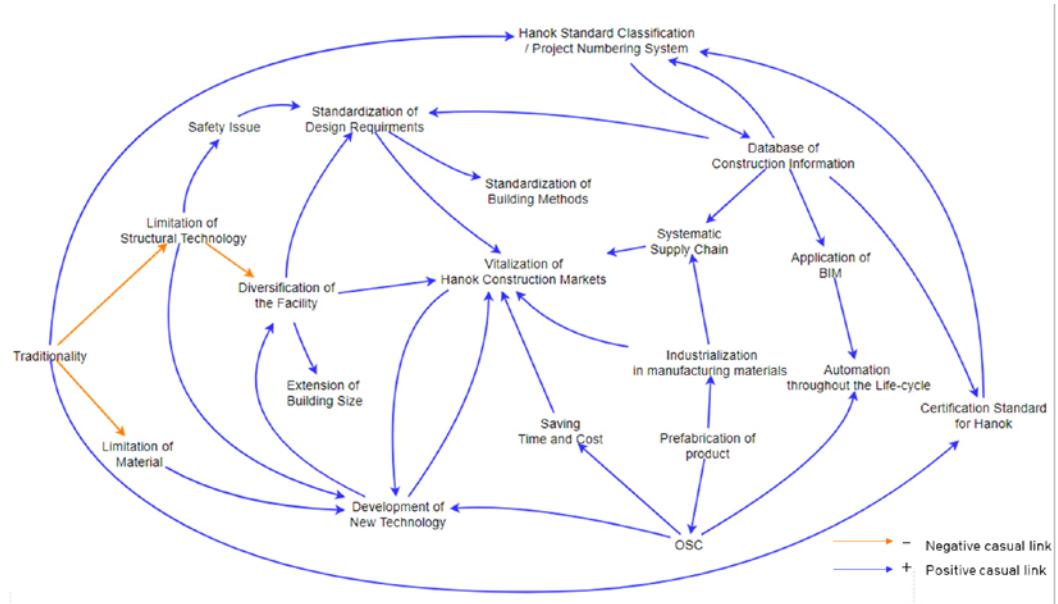


Figure 4. Casual diagram of modernized Hanok research project

In the previous chapter, four types of influencing variables related issues and the five technical strategies were discussed. In this chapter, based on the factors described above, the overall context of modernized Hanok research is reviewed and comprehensive technology strategies are summarized through causal diagrams that can identify causal relationships with each factor (Figure 3).

The traditional value of Hanok is very important, but, due to its material and structural technology limitations, it is difficult to diversify facilities and popularize Hanok architecture. Therefore, it is necessary to resolve these problems by developing various technologies within the scope of maintaining its traditional uniqueness. Thus, the classification that reflects the characteristics of the Hanok should be used to create and manage the certification standard of Hanok.

In addition, as Hanok project takes more time and cost than other wooden building, it is needed to be applied more actively the prefabrication technology and OSC method, which should utilize standard supply chain, BIM and automation technology based on accumulated database and PNS.

To this end, for the long-term technological development of Hanok, standardization of design standards and building methods based on abundant databases will be a way to utilize and popularize hanok technology more efficiently while keeping the value of Hanok well.

5. CONCLUSION

There has been an effort to popularize the development of technology for hanok wooden buildings as the interest in hanok has been increasing. To this end, the purpose of this paper was to identify influencing factors and issues of Hanok technology first and then suggest technology strategies of Hanok.

The influencing factors are defined as ‘timber frame type’, ‘architectural style’, ‘facility type’, and ‘building size’ and their issues are analyzed as ‘diversification of building method’, ‘conservation of tradition & development of new technology’, ‘standardization of design requirement’ and ‘standardization of building methods’.

Based on the influencing variables, the five keywords of technology were proposed as ‘standard supply chain protocols’, ‘prefabrication & OSC’, ‘industry standard classification’, ‘knowledge repository & standard performance’ and automated life-cycle’.

Finally, the overall context of modernized Hanok research is reviewed and comprehensive technology strategies are summarized through causal diagrams. More actual data shall be accumulated based on the Hanok classification and automation technology, prefabrication and OSC method should be applied more actively. In addition, standard design requirements and building methods including new materials and technology of Hanok can be proposed to promote popularization of Hanok technology.

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XVIII. BIG DATA AND AI LEARNING II (F3)

Field Test of Automated Activity Classification Using Acceleration Signals from a Wristband

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Abstract: Worker's awkward postures and unreasonable physical load can be corrected by monitoring construction activities, thereby increasing the safety and productivity of construction workers and projects. However, manual identification is time-consuming and contains high human variance. In this regard, an automated activity recognition system based on inertial measurement unit can help in rapidly and precisely collecting motion data. With the acceleration data, the machine learning algorithm will be used to train classifiers for automatically categorizing activities. However, input acceleration data are extracted either from designed experiments or simple construction work in previous studies. Thus, collected data series are discontinuous and activity categories are insufficient for real construction circumstances. This study aims to collect acceleration data during long-term continuous work in a construction project and validate the feasibility of activity recognition algorithm with the continuous motion data. The data collection covers two different workers performing formwork at the same site. An accelerator, as well as portable camera, is attached to the worker during the entire working session for simultaneously recording motion data and working activity. The supervised machine learning-based models are trained to classify activity in hierarchical levels, which reaches a 96.9% testing accuracy of recognizing rest and work and 85.6% testing accuracy of identifying stationary, traveling, and rebar installation actions.

Key words: activity recognition, continuous filed data, acceleration, automation, safety

1. INTRODUCTION

Activity analysis is a technique for monitoring, recognizing, and assessing the activities of workers during ongoing projects(Thomas & Mathews, 1986). This technique has a great potential for improving construction productivity, as it efficiently measures the time spent on specific activities and identifies any issues that hinder labor productivity (Gouett, Haas, Goodrum, & Caldas, 2011). Activity analysis has been used to identify potential safety risks by combining with hazard assessment techniques, such as job hazard analysis (Rozenfeld, Sacks, Rosenfeld, & Baum, 2010). However, as this approach relies on manual observation, significant time and effort are required for data collection and analysis.

Recent advancements in automation technologies in construction have provided considerable opportunity for measuring and tracking workers' activities by using sensor data and analytics techniques, such as machine learning. In comparison with conventional observation methods, automated data collection and analysis for activities is not only time-saving and objective but also applicable to the collection of massive data from multiple workers. Among these sensors, wearable devices equipped with accelerometer are gaining attention, as they allow motion data collection (i.e., accelerations) without interfering with ongoing work. Recently, remarkable achievements on acceleration-based action recognition have been obtained using different wearable devices, such as single IMU sensor (Joshua & Varghese, 2014), smartphone (Akhabian & Behzadan, 2016), and wristband (Ryu, Seo, Jebelli, & Lee, 2018). These studies have applied machine learning approaches to classify diverse predefined construction activities automatically on the basis of acceleration signals, which have reported high performance on classifying actions. Although these previous research efforts have tested the usage

potential of IMU data (i.e., acceleration signals) for activity analysis, the applicability of these approaches in practice has not been fully tested, as they rely on the data collected from controlled experiments by repeating specific types of activities (Yan, Li, Li, & Zhang, 2017). The data collected during actual construction tasks are noisy and unstructured due to the dynamic nature of construction work. The movements of workers vary depending on site conditions even for same tasks, leading to potential errors in acceleration-based action recognition. Moreover, activity types are difficult to predefine in practice, as construction activities are unstandardized. Considering these remaining challenges, further investigation of these approaches in practice is required to improve the practical applicability of automated activity analysis using acceleration-based action recognition approaches.

In this regard, the study attempts to validate acceleration-based action recognition protocol for field construction tasks with continuous data. In particular, a wristband (i.e., Apple Watch) was selected to collect acceleration data, as many construction activities are hand-dominant; thus, acceleration signals from a wristband efficiently represent dynamic activities involving complicated arm movements (Ryu et al., 2018). We collected acceleration data from two rebar workers by attaching an Apple Watch to their dominant hands during concrete formwork of a housing project in Hong Kong. Then, the collected data were used to test the performance of action recognition based on machine learning approaches. Potential issues when applying these approaches in practice were discussed on the basis of the results.

2. LITERATURE REVIEW

2.1. Monitoring human activity via sensors

Activity analysis can evaluate and improve the safety (Chhokar & Wallin, 1984) and productivity (Haas, Borcherding, Allmon, & Goodrum, 1999) in construction. Previous practices mainly rely on safety supervisors to assess the behavior of workers manually; thus, the procedure is time-consuming (Hendrickson, Hendrickson, & Au, 1989) and subjective (Mattila, Hyttinen, & Rantanen, 1994). With the improvement of sensor technologies, video- and sensor-based approaches have been demonstrated feasible for monitoring construction workers. Vision-based approaches require the cooperation of the surveillance system and computer vision-based algorithms, which generate the models from videotapes for identifying posture and action types. Consequently, experts can assess worker health (Han & Lee, 2013) and estimate productivity (Peddi, 2008) in an automatic and effective protocol. Risk assessment can also be accomplished through vision-based ergonomic analysis (Seo, Han, Lee, & Kim, 2015). Vision-based methodologies have not only gained abundant achievements in motion monitoring and analysis but also been proven to have a great potential in the construction domain. However, the application of vision-based approaches is limited by the construction environment. For instance, weak light condition and obstruction profoundly disturb the video quality, thereby declining the model performance (Seo et al., 2015). To address this limitation, researchers have developed various sensor-based methods, such as location sensor-based and body-worn sensor approaches, for assessing construction workers' activities (Ryu et al., 2018). The location sensor includes, but is not limited to, a global positioning system, radiofrequency identification, ultra-wide band, and wireless local area network, which allow the tracking of workers' activities in the construction site (Aryan, 2011; Montaser & Moselhi, 2014; van Diggelen, 2002; Woo et al., 2011). However, the location information is insufficient for action recognition and posture assessment. On this basis, the body-worn sensor, particularly IMUs, has drawn attention and demonstrated its feasibility in acceleration data collection and action classification (Akhavian & Behzadan, 2016).

2.2. Accelerometer-based action recognition research

As a portable sensor for tracking triaxial acceleration signals, the accelerometer is widely embedded in wearable devices, which is a broadly used sensor in activities recognition due to the low cost, low energy-consuming and low interference (Lara & Labrador, 2012). Human action recognition divides the annotated signal streams into patterns and then extracts acceleration data into feature variables, which are set as the inputs of action classifiers (Chernbumroong, Atkins, & Yu, 2011). The high performances were reported on recognizing daily activities such as walking, jogging, sitting, and standing (Kwapisz, Weiss, & Moore, 2011; Ravi, Dandekar, Mysore, & Littman, 2005). Meanwhile, the successful application in construction comprises fall detection (Lim, Park, Lee, & Lee, 2015; Yang, Jebelli, Ahn, & Vuran, 2015) and activity classification (Joshua & Varghese, 2010).

The position for mounting the sensor is varied and significantly affects the analysis (Bao & Intille, 2004). Attaching the accelerometer to the waist is a reasonable option because waist motion can represent the trend of body movement. Joshua and Varghese (2014) used a waist-worn acetometer to develop an acceleration-based classification protocol. The high performance of the scheme demonstrated that waist-mounted acceleration is suitable for action recognition. However, construction-related action comprises several micromovements that are difficult to capture by waist acceleration, such as wrist and upper-limb movements. On this basis, researchers suggested attaching a wearable device equipped with accelerometer on dominant waist to track acceleration information. The feasibility has been proven in multiple publications (Chernbumroong et al., 2011; Koskimaki, Huikari, Siirtola, Laurinen, & Roning, 2009; Lara & Labrador, 2012; Ryu et al., 2018). Meanwhile, IMU embedded wristband-type device (e.g. smartwatch) is an idea device for collect hand movement in consistent position with little discomfort (Weiss, Timko, Gallagher, Yoneda, & Schreiber, 2016). Joshua and Varghese (2014) introduced IMU-based activity classification into the field and developed action identification models with the motion data collected from the waist and lower arms from carpentry and ironwork. As the prediction accuracies reached 90.07% and 77.74% for ironwork and carpentry, respectively, the study validated that wear-based activity analysis can be applied for field-collected acceleration data. However, several gaps existed in applying acceleration-based action identification in the construction site: 1) Previous studies removed the junction among the segments in the training material. While, the data collected from the site are supposed to be continuous and noisy. 2) Comparing with the action types conducted in instructed environment, the activity categories are more complex and diverse.

3. METHODOLOGY

This research aims to test a wearable accelerometer-based approach for automatically recognizing construction workers' activity category on the basis of the continuous data collected from the field. This research focuses on rebar work, one of the most standard construction activities on the site, which consists of complex body activities and numerous micromovements in the wrist joint. To analyze the complicated acceleration signals captured from the IMU-embedded wearable sensors, multiple significant operations, such as optimizing the features, segment size, and training algorithms, are considered to achieve high performance. The training and validation procedure comprises the following steps: 1) collecting and labeling data, 2) segmenting data and extracting feature variables, 3) training classifiers, and 4) validating the model.

3.1. Collecting and labeling data

This project arranged a long-term data collection from multiple workers in two ongoing sites and constructed a large-scale database on continuous construction actions. During data collection, the participants were equipped with an Apple Watch in the dominant hand and a GoPro camera at the chest. With the self-developed WatchOS app, the Apple Watch can cumulatively read 3D inertial data, which are transferred to the laptop afterward. The GoPro camera was used to target the hands and record simultaneously for identifying the activity category. The Figure 1 shows the photos during filed data collection. Field data collection lasted 19 days in total, which finished in three collecting periods from November 2018 to March 2019. The project acquired around 498 h of videotapes and 2.83 billion acceleration sets from 18 different workers, including rebar, concrete, and form workers. Prior to the labeling of acceleration signals, data quality assessment was conducted to indicate the following failures of data collection: 1) Data capture failure. Participants took off equipment due to disturbance, and equipment stopped working due to misoperation or accidents. 2) Poor-quality videotapes. Videotapes could not provide the action information due to poor light conditions, and the chest-mounted camera could not record the wrist movement. 3) Data transmission or storage failure. To ensure the high quality of data, training and testing materials were constructed from two rebar workers' acceleration signals collected on March 4, 5, and 8, which are strictly continuous and independent.



Figure 1. Site photos for data collection

Table 1. Rebar activity taxonomy

Activity			Activity examples
Level 1	Level 2	Level 3	
Break	Stationary	Standing/Sitting	Standing or Sitting
Work	Traveling	Transportation	Horizontal, vertical, included movement, jumping, skipping, going upstairs/downstairs, climbing up/down a ladder
		Transferring materials and tools	Dynamical wrist movement while traveling, carrying materials and tools in horizontal, vertical, and inclined movement, carrying materials and tools while going upstairs or downstairs, climbing up or down a ladder
	Rebar installation	Rebar preparation	Cutting and bending
		Rebar placing	Placing, adjusting, and lifting
		Rebar tying	Fixing and tying
		Supplement work	Irregular wrist movement, lifting materials and tools, squatting, standing up, rotating trunk
		Uncertain operation	Action with unclear video recording

The acceleration and video streams include the unique timestamps when recording, through which the inertial response can be synchronized with the predetermined action category (Table 1) on the basis of the videotapes. Considering the dynamic nature of construction work, the labeling procedure is challenging since the activities are transmitted too frequently to identify each pattern and the

transmission pattern. The error will be huge considering that thousands of junctions exist in the hours of data. Therefore, the junction between action patterns will be assigned the label of later patterns in the labeling procedure. As long as the activity is detected as changing, the assigned label will change correspondingly. The predefined taxonomy includes two divisions. The activity comprises exercises hierarchically from level 1 to level 3 with corresponding construction-related responses. Meanwhile, the activity examples refer to the basic movements that support identifying activities in ergonomic perspective. For instance, if the worker's action is regarded as cutting rebar through the videotapes, the activity information could be concluded as rebar installation and rebar preparation in level 2 and level 3 respectively.

3.2. Segmenting data and extracting feature variables

Considering the nature of human actions, continuous acceleration data should be divided into equal segments to represent the actions in a particular duration. This study used a sliding window approach to construct optimal action windows because the classification performance relies on the window size (Banos, Galvez, Damas, Pomares, & Rojas, 2014). Bonomi, Goris, Yin, and Westerterp (2009) demonstrated that a 6.4 s segment is the optimal window for classifying various motions, such as lying, sitting, standing, dynamic movement, walking, running, and cycling. The present study tested a diverse segment duration from 1 s to 6.5 s and selected the best performance model as the optimal classifier. Meanwhile, the data operating procedures included a 50% overlap when conducting the sliding window method, which was demonstrated as necessary in handling continuous motion signals (Bao & Intille, 2004; Ryu et al., 2018).

Labeled action patterns were extracted as feature variables on the basis of vital signal properties to distinguish activity patterns (Figo, Diniz, Ferreira, & Cardoso, 2010). Time- and frequency-domain features are the most widely used features for analyzing human actions (Preece et al., 2009). Time-domain features include, but are not limited to, mean value, maximum value, median, and variance, which reveal the statistical characteristics of the motion signals (Bao & Intille, 2004). Meanwhile, frequency-domain features, such as energy and entropy, measure the acceleration streams in the perspective of frequency by utilizing fast Fourier transform and are frequently utilized to evaluate action complexity in acceleration-based activity analysis (Preece et al., 2009). Ten broadly used significant features variables (Ryu et al., 2018) are employed, which covers eight time-domain features and two frequency-domain features (Table).

Table 2. List of feature variables

Feature type	Feature variable (including x, y, and z axes)
Frequency-domain features	Entropy
	Energy
Time-domain features	Mean value
	Skewness
	Maximum value
	Minimum value
	Range
	Standard deviation
	Kurtosis
	Correlation between two axes

3.3. Training classifiers and validation

This study used supervised machine learning methods to train the pre-labeled feature variables and generated classifiers for automatically identifying workers' action division. With the Classification Learner app in MATLAB (2019a, MathWorks), a platform implementing several classification training schemes, training and assessment were conducted productively. On the basis of the assessment, three

classifiers generate the highest identification rate, namely, 1) ensemble bagged trees (Dietterich, 2000), 2) support vector machine (SVM) (Hsu & Lin, 2002), and 3) k-nearest neighbor (kNN) (Sutton, 2012).

The validation involves testing the model prediction performance with additional data. The two typical evaluating schemes are n-fold cross-validation and holdout validation. In n-fold cross-validation, the entire dataset is initially randomly split into equal-size subsets, one subset of which is the testing set and the rest of the (n-1) subsets are set as a training set. Each trial generates a classifier from training data. The prediction accuracy is the correct prediction rate by inputting the test data in the trained classifier. The n-fold cross-validation adopts an overall accuracy after being run over all the test datasets, which means n times in total (Kohavi, 1995). Holdout validation is another assessment protocol for large-scale data. The algorithms randomly extract a specific part (held-out percentage) of data as test dataset and trains the model with the rest of the data. The performance is evaluated by the test data, and the algorithm trains all data to obtain the final model. The overall accuracy is also calculated by the correct prediction rate, and all data train the generated classifier.

The overall prediction accuracy is an indicator for simultaneously measuring the model performance for all categories, which however cannot measure incorrect prediction cases among the categories. Therefore, the confusion matrix is introduced as the supplemental approach for quantifying the difficulty of distinguishing one category from another class of actions. The validation provides significant indications to adjust the window size, modify the category library, and promote the algorithms.

4. TESTING RESULTS

Part of continuous data period with high quality was selected as analysis objective in the study due to the low quality of raw data. The dataset consisted of the action data from two different rebar workers in three different working periods, lasting for 13.6 h and with 145,688 sets of data. Multiple data sessions were individually extracted as features, which would be combined as comprehensive dataset. For test demand, a period of around 1 h was randomly extracted as the test dataset. The training dataset contained the rest of the datasets. On the basis of different category levels, the testing procedure covered three classifiers. Classifier 1 was for recognizing activity level to classify ineffective and effective work; classifier 2 was for distinguishing stationary, traveling, and immobile working actions; and classifier 3 was for identifying basic task actions. The training procedure ran multiple training models with various window sizes. A 10% held-out validation measured the performance of each trained model. The training and testing results were presented in Table 3 to Table 5.

Table 3. Confusion matrix of Classifier 1 (best) with 0.5 s window size

Level 1 Activity				
Classifier: Ensemble bagged trees				
Work	Work	Break	Recall	
Work	26177	177		99.3%
Break	419	9649		95.8%
Precision	98.4%	98.2%		

*Training accuracy: 98.4% Test accuracy: 96.9%

Table 4. Confusion matrix of Classifier 2 (best) with 0.5 s window size

Level 2 Activity				
Classifier: Ensemble bagged trees				
Work	Rebar installation	Traveling	Stationary	Recall
Rebar installation	7301	302	49	95.4%
Traveling	946	1925	16	66.7%
Stationary	120	18	3891	96.6%
Precision	87.3%	85.7%	98.4%	

*Training accuracy: 90.0%

Test accuracy: 85.6%

Table 5. Confusion matrix of Classifier 3 (best) with 0.5 s window size

Work	A	B	C	D	E	F	G	H	Recall
A = Uncertain operation	0	3	0	0	0	0	3	1	0.0%
B = Supplement work	1	1966	264	61	52	13	324	74	71.4%
C = Rebar tying	0	387	1416	52	55	0	108	48	68.5%
D = Rebar placing	0	165	72	946	14	2	28	6	76.7%
E = Rebar preparation	0	185	72	16	1125	2	115	21	73.2%
F = Transferring materials and tools	0	131	31	8	7	46	168	7	11.6%
G = Transportation	0	396	111	9	26	13	1911	20	76.9%
H = Standing/sitting	0	59	14	0	7	1	11	3995	97.7%
Precision	0.0%	59.7%	71.5%	86.6%	87.5%	59.7%	71.6%	95.8%	

*Training accuracy: 78.3%

Test accuracy: 55.9%

5. DISCUSSIONS

The result shows that ensemble bagged tree has the best performance with an optimal window size of 0.5 s for each classifier. Previous research (Ryu et al., 2018) stated that a large window size generates high performance, which is contrast to the present case. One of the possible reasons is that the basic task level actions occur rapidly in the real construction site. For example, in rebar work, the worker typically bends rebar for 2 s and conducts supplement work, such as lifting, in the following second. Therefore, a small window size can help in efficiently distinguishing the categories under extensive situations.

Table 3 indicates the high performance in recognizing break and work for rebar task. The training and testing accuracies are 98.4% and 96.9%, respectively. Thus, the trained classifier has a 96.9% possibility of correctly detecting break and work with the testing data. Meanwhile, the recall and precision ratio for the individual category is over 95%. Therefore, Classifier 1 can be an objective and efficient tool for measuring the resting time and working duration in the field.

Table 4 shows the validation results for Classifier 2, i.e., stationary, traveling, and rebar installation activities. The overall training and test accuracies reach 90.0% and 85.6%, respectively, thereby validating the feasibility of using the model in field situation to recognize whether the worker is standing and sitting for rest, traveling in the site, or installing the rebar. However, the confusion matrix in Table 4 indicates that 33.3% of traveling activity cannot be correctly predicted as traveling, which is unacceptable in field application. The main confusion is observed in the traveling and rebar installation categories, which means that several small movements exist when working at the certain spot. Either the algorithm does not detect micro-traveling or the actions are not appropriately annotated.

Table 5 shows the performance of Classifier 3 for rebar activities. The overall accuracy for Classifier 3 is 78.3% with a test accuracy of 55.9%, which are relative lower than the application threshold. Meanwhile, the confusion matrix indicates that the categories of rebar tying and transferring materials and tools have misprediction rates of 31.5% and 88.4%, respectively. The detection errors are mainly caused by supplement work. Hence, supplement work comprises numerous activities similar to other activities. Other reasons for the poor performance include the following: 1) The camera cannot capture the minimal rest or hand movement during rebar work; thus, distinguishing different categories is difficult in the data labeling stage. 2) The window size is too small to remove the noise from the junction that frequently occurs during work. 3) The uncertain movement category consists of numerous observations, which induce certain confusions when recognizing activities.

6. CONCLUSIONS

This study collects strictly continuous data from the construction site to validate the feasibility of action recognition algorithm and generate the classification model in the activity and action levels for rebar work. The activity indicates the construction nature of movement and the action related to motion features of elemental exercise. The activity includes three levels of category. Level 1 activity includes rest and work and determines the objective productivity by detecting whether the workers are working or resting. The results show that the testing accuracy of current classifiers reaches 96.9%. Thus, Classifier 1 can efficiently classify work and rest with external data from other rebar workers in filed situations and meets the demand for detect low productivity issue in the field. Level 2 activity has acceptable overall accuracy for classifying stationary, traveling, and rebar installation. The training and test accuracies in this level are 90.0% and 85.6%, respectively. Stationary action includes standing and sitting in the jobsite. Traveling covers activities with changing position in the site, such as walking and transferring materials. Rebar installation refers to activities at a constant position, such as bending and cutting rebars at a stable spot. Level 3 activity for rebar work has a 78.3% overall training accuracy and 55.9% test accuracy. The classifications of supplement work and rebar installation can evaluate the contribution on core construction work, which can help managers assign skilled and experienced workers to critical procedures, such as the rebar installation. Consequently, productivity will be improved.

Level 1 and level 2 activities have acceptable performance and can provide valuable information to meet the demands of managers and workers. Level 3 activity and action level classifier are unsuitable for field application due to poor performance. The misclassification between categories is high and is caused by the confusion between traveling and rebar installation activities, since minimal and short-duration movements exist during work.

The current result demonstrates the feasibility of applying the proposed action recognition protocol in filed construction. In this regard, the construction action would be classified instantly during the site work, which helps manager detect the low productivity activity efficiently, such as long time resting or traveling. As a result, the project procedure could be corrected in the perspective of productivity. Filed data collection is the most challenging part. The dataset employed in this study is still limited, 1) few workers' acceleration information are included, which is not able to eliminate the human variance; 2) this study only discuss the rebar work, which is not adequate for checking field project productivity. The future work will expand the dataset by adding data collected from additional workers to reduce the human variance. To remove the junction noise in continuous work, data processing methods will be adopted. For instance, post-processing is an ideal method for removing prediction class accidentally appearing in a series of continuous data. Meanwhile, additional machine learning-based algorithms, such as deep learning-based methods, will be validated. The present result indicates that a short window size contributes to a high overall result, whereas a large window size reduces the internal misclassification error among the categories. A trade-off will be discussed to balance overall and internal performances.

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XIX. INTELLIGENT CONSTRUCTION AUTOMATION II (G1)

Real-time automated detection of construction noise sources based on convolutional neural networks

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Abstract: Noise which is unwanted sound is a serious pollutant that can affect human health, as well as the working and living environment if exposed to humans. However, current noise management on the construction project is generally conducted after the noise exceeds the regulation standard, which increases the conflicts with inhabitants near the construction site and threats to the safety and productivity of construction workers. To overcome the limitations of the current noise management methods, the activities of construction equipment which is the main source of construction noise need to be managed throughout the construction period in real-time. Therefore, this paper proposed a framework for automatically detecting noise sources in construction sites in real-time based on convolutional neural networks (CNNs) according to the following four steps: (i) Step 1: Definition of the noise sources; (ii) Step 2: Data preparation; (iii) Step 3: Noise source classification using the audio CNN; and (iv) Step 4: Noise source detection using the visual CNN. The short-time Fourier transform (STFT) and temporal image processing are used to contain temporal features of the audio and visual data. In addition, the AlexNet and You Only Look Once v3 (YOLOv3) algorithms have been adopted to classify and detect the noise sources in real-time. As a result, the proposed framework is expected to immediately find construction activities as current noise sources on the video of the construction site. The proposed framework could be helpful for environmental construction managers to efficiently identify and control the noise by automatically detecting the noise sources among many activities carried out by various types of construction equipment. Thereby, not only conflicts between inhabitants and construction companies caused by construction noise can be prevented, but also the noise-related health risks and productivity degradation for construction workers and inhabitants near the construction site can be minimized.

Key words: Construction noise, Real-time automated detection, Convolutional neural network, Short-time Fourier transform, Temporal image processing

1. INTRODUCTION

Environment pollutants (e.g., greenhouse gas, noise, odor, waste) from industrial activities cause critical social problems that undermine the quality of life and environmental rights of humans [1, 2].

Among the various environmental pollutants, especially, noise (i.e., unwanted, unpleasant, and loud sounds) generated from construction sites can directly and immediately affect the people around the noise source [3, 4]. Moreover, as construction projects have become more complex and larger, the construction noise from various types of heavy construction equipment throughout the construction period (i.e., several months to years) can damage health of construction workers and inhabitants near the construction site along with their working and living environment [5-7]. Despite the strengthened regulations and management guidelines on noise emissions to address these noise issues [8-10], construction noise has been provoking a stream of many complaints and conflicts between inhabitants and construction companies that cause delay in the construction project [11, 12]. In addition, construction noise causes health problems such as hearing loss, and productivity degradation through decreased concentration of construction workers located directly next to the noise source [7, 13]. Consequently, to minimize the deterioration in quality of life and potential conflicts arising from inhabitants, and to ensure the productivity and safety of the construction workers or labors, construction managers need to manage the level of construction noise as much as possible. However, until now, construction noise in South Korea has been managed and monitored only for a short period of time (e.g., three times of five-minute measurements) after the noise complaints occur. Therefore, during the rest period of time, the unmanaged construction noise can constantly affect to construction workers and inhabitants. Due to this poor management of construction noise, inhabitants near construction sites as well as construction workers, are still exposed to unnecessary and unpleasant noise during the entire construction period. To overcome the limitations of the current noise management methods, the level of construction noise and the activities of noise generating construction equipment, which is the main source of the construction noise, need to be monitored and managed throughout the construction period in real-time.

With the necessity of managing both construction noise and equipment in real-time, several previous studies proposed different methods for identifying construction equipment or noise using various deep learning methods based on the following two data format: (i) audio data; and (ii) visual data. First, some studies classified the activities of construction equipment and analyzed the effects of noise on humans by analyzing the characteristics of the audio data so as to recognize construction equipment or assess construction noise. Cheng et al. [14] converted the audio data into a time-frequency representation using a short-time Fourier transform (STFT), then classified the activity of each construction equipment using an support vector machine (SVM). Abdoli et al. [15] classified the environmental sounds (e.g., drilling, engine idling, jack-hammers) based on the audio data using a 1-dimensional convolutional neural network (CNN) without data preprocessing. Lee et al. [16] and Ballesteros et al. [17] analyzed the characteristics of construction noise (i.e., sound pressure level and frequency) according to the type of construction stage and equipment, and assessed the impact of construction noise (such as annoyance and stress) on construction workers or general public. Second, several studies identified the types and activities of construction equipment by analyzing visual data to measure and monitor the performance of construction equipment. Kim et al. [18] proposed a framework to identify the interactive operations between excavators and dump trucks based on a comprehensive visual dataset of activities by using a tracking-learning-detection method. Fang et al. [19] extracted feature maps from visual data and improved the accuracy of identifying construction equipment and workers in real-time using improved faster region-based CNN (Faster R-CNN). Golparvar-Fard et al. [20] collected spatio-temporal visual features from the visual data of a single piece of construction equipment, then identified the activity through the distributions of the spatio-temporal features using an SVM.

Although these previous studies identified the types and activities of construction equipment by analyzing audio or video data using deep learning methods, following limitations still remain. First, previous studies successfully analyzed the characteristics and effects of construction noise on construction equipment only using the audio data, but they did not classify or manage construction noise in real-time. Second, previous studies identified the types or activities of the construction equipment only using the visual data, but there are limitations in identifying multiple noises generating construction equipment in real-time on a large and complex construction site. In these studies, some of them were failed to identify the activity of construction equipment because they analyzed 2-dimensional data (i.e., single image) which is non-temporal. Others successfully identified the activity of construction equipment, however, they still had a limitation in identifying multiple construction equipment at the same time. Third, since previous studies only analyzed either the audio or video data through deep learning in order to judge the types and activities of the construction equipment, it was hard to judge the noise generating construction equipment practically at the actual construction sites. That is, when only

audio data is analyzed, the type and activity of the equipment can be identified, but the actual location of the equipment remains unknown. On the other hand, when only visual data is analyzed, the type, activity, and location of the equipment can be identified, but the magnitude of the noise remains unknown. Consequently, to manage the construction noise practically and effectively in real-time, it is necessary to simultaneously analyze the temporal audio and visual data to detect the multiple noises generating construction equipment at a construction site. Therefore, this study aimed to propose a framework for automatically and systematically detecting the noise source on the whole construction site in real-time by classifying the noise source based on the temporal audio data and detecting it based on the visual data through CNN-based deep learning.

2. METHODS AND MATERIALS

In this study, the proposed framework for real-time automated detection of construction noise sources consists of four steps (refer to Fig. 1). First, the noise sources in the construction site should be defined according to the types of equipment and their activities. Second, the audio and visual data on the construction equipment should be preprocessed so as to be input of the audio CNN and the visual CNN. Third, the construction noise should be automatically classified based on the audio input data by feeding them into the audio CNN in order to determine the current noise source in the construction site. Fourth, the construction equipment and activities which are determined to be noise sources should be detected on the video of the construction site by feeding visual input data into the visual CNN. As a result, by utilizing the video of the construction site, the proposed framework can make it possible to automatically detect where the construction noise is generated in real-time. Details of each step are described below.

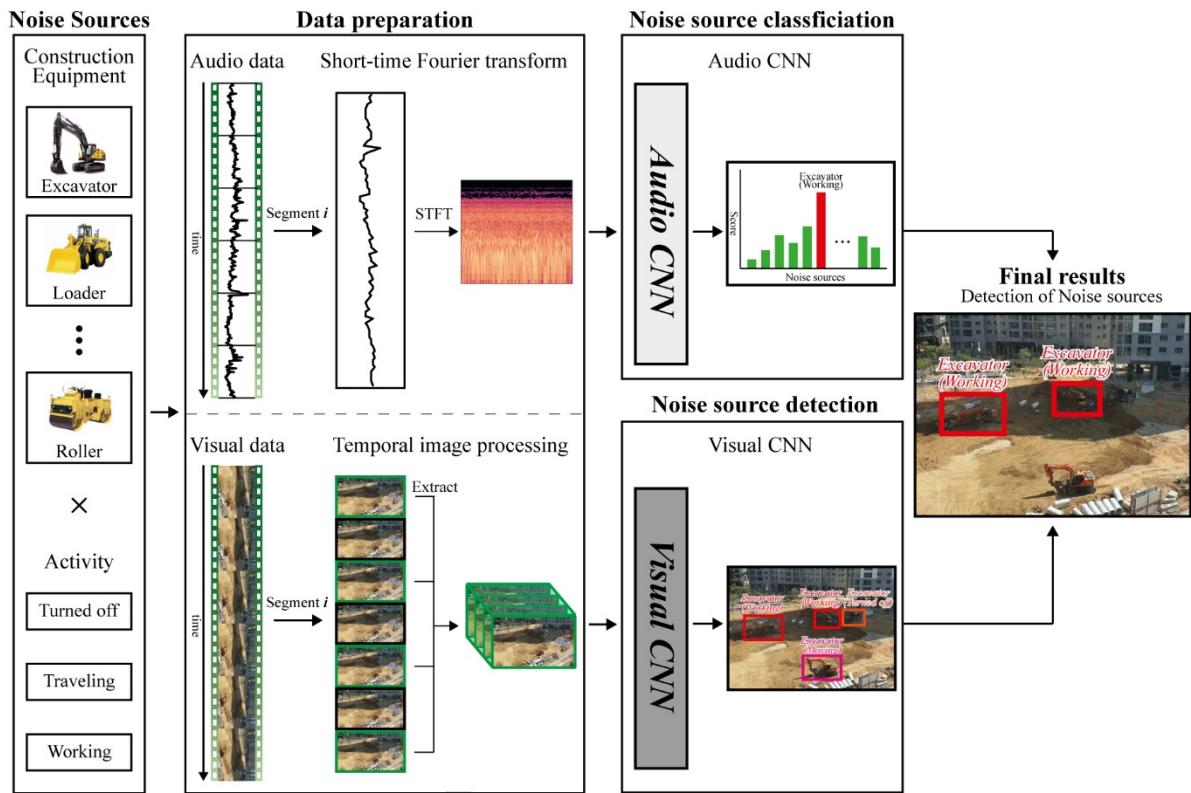


Figure 1. The proposed framework for a real-time automated detection of construction noise sources

2.1. Step 1. Definition of the noise sources

On construction sites, various types of heavy construction equipment generate noises which are different in amplitude, frequency, and wavelength while performing a particular activity [16]. Therefore, this study defined noise sources according to the types of heavy construction equipment and their activities. The types of heavy construction equipment can be defined in terms of the noise-generating construction equipment regulated under the *Noise and Vibration Control Act* of South Korea [21]:

excavator, roller, loader, breaker, earth auger, pile driver, and dump truck. In addition, the activities of each type of construction equipment can be defined by taking into account the different characteristics of the noises of each activity: turned off, traveling, and working. However, since a roller and dump truck among the defined types of heavy construction equipment, travel and work at the same time, their working activity is considered as a traveling activity. As a result, the noise sources in this study are defined by seven types of construction equipment with their activities, as shown in Table 1.

Table 1. The defined noise sources

Types	Activities		
	Turned off	Traveling	Working
Excavator	○	○	○
Roller	○	○	-
Loader	○	○	○
Breaker	○	○	○
Earth auger	○	○	○
Pile driver	○	○	○
Dump truck	○	○	-

2.2. Step 2. Data preparation

In order to extract the feature of the noise and movements of the noise sources, the audio and visual data on the noise sources should be collected and preprocessed. The audio and visual data on the noise sources can be collected from audio and video recordings on the construction site. When the noise is generated from the construction equipment, the audio signal of the generated noise changes over time according to the pattern of the activity. Moreover, the activity of the construction equipment cannot be detected when using a single image, as the defined types of construction equipment generate noises with movements or actions that can cause changes in each sequence of the video. Therefore, to include the information of those changes over time, each segmented frame from the audio and video recordings with the proper length of time should be preprocessed into 3-dimensional data including width, height, and color channels to then serve as input data for the CNNs. Towards this end, the proposed framework transforms the collected data using the STFT for the audio data and temporal image processing for the visual data.

Firstly, to extract the feature from the audio data, the audio signal should be converted into the form of a time-frequency domain using the STFT. The discrete Fourier transform (DFT), which is usually used for spectral analysis of the signal, can only extract the frequency domain information on the audio signals. On the other hand, the STFT, which is a sequence of the DFTs of the divided signals with a certain window size in time, can extract the time-frequency domain information that makes it possible to track the changes of the frequency properties of the audio signal over time. To perform the STFT on the audio data, first, the collected raw audio data should be sampled to change the continuous signal into discrete frames. After the sampling of the raw audio data, the discrete frames should be segmented to make the frameset of which to calculate the STFT. The STFT of the frameset can be obtained by dividing the frameset with the window size and then multiplying each divided frames by a window function (refer to Eq. (1)). As a result, the raw audio data can be transformed into 3-dimensional representation to be the input data for the audio CNN. As shown in Fig. 2, the audio input data indicates the amplitude of a certain frequency at a certain time that can be shown as the intensity of the color in the image. For the training dataset, the transformed frameset should be labeled with the defined noise sources.

$$X(k, t) = \sum_{m=0}^{M-1} w(m)x(m + Zt)e^{-2\pi jmk/M} \quad (1)$$

where $X(k, t)$ is the value at frequency k and time t , m is the signal frame, M is the window size, $w(m)$ is the window function, $x(m + Zt)$ is the original divided signal, and Z is the parameter of a window stride.

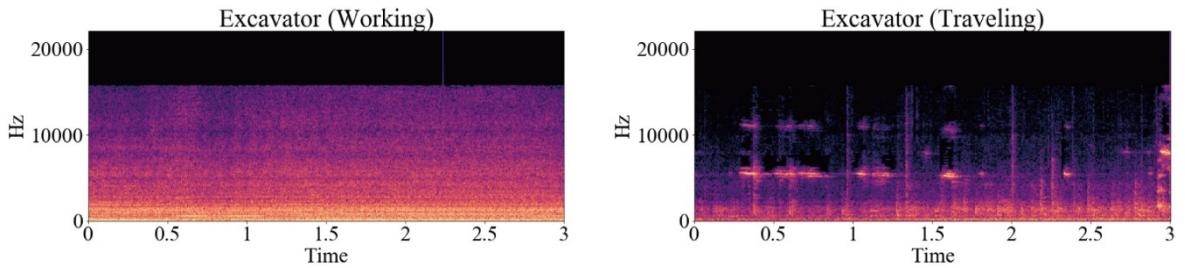


Figure 2. An image example for the STFT of the construction equipment

Secondly, the video data should be transformed to extract the feature. Video can be described as a set of image frames. Accordingly, actions in the video can be regarded as the temporal change of the color of the pixels. Therefore, in order to consider these changes in the input data for the visual CNN, the temporal image processing that concatenates multiple image frames into a single set of image frames is used for generating the visual data. The temporal image processing can start by sampling the image frames from the video. In addition, to recognize the actions from the sampled image frames, they need to contain enough length of time from the first to the last image frames while reflecting definite changes in pixels. If too many image frames are sampled, however, the CNN cannot operate in real-time due to excessive computational demands. Accordingly, after sampling the image frames, a subset of the sampled image frames should be extracted at particular frame intervals. Then, the extracted image frames from the subset should be concatenated into a single set of input data for the visual CNN.

For example, if the subset frames are extracted at eight intervals from 25 frames of the video whose width and height is 416×416 , the visual input data will be the concatenated four frames (i.e., 1st, 9th, 17th, and 25th) with the size of $416 \times 416 \times 12$ (i.e., width \times height \times (RGB channels \times four frames)). As a result, the visual input data can reflect enough length of time during the activity of the construction equipment with less amount of data. Just like the audio input data, the visual input data can be also transformed into 3-dimensional data and each transformed data should be labeled with the defined noise sources for the training dataset.

2.3. Step 3. Noise source classification using the audio CNN

As CNNs have been proven to be effective in image classification, there have been increasing attempts to analyze audio signals using CNN algorithms (i.e., AlexNet, Inception, VGG, and ResNet) and the results were promising [22]. In order to determine what kind of activity of the construction equipment was the source of the current noise, this study proposed the audio CNN as a real-time automated classification algorithm by using the AlexNet which significantly outperformed the other prior algorithms.

In this study, the AlexNet which consists of five convolutional layers for feature extraction, three fully connected layers for classification, and three max-pooling layers for subsampling is applied to the audio CNN. To prevent the gradient vanishing which interrupts the training of the network, the ReLU (Rectified Linear Unit) is used as the activation function of overall neurons. On the other hand, the output of the last fully connected layer can be calculated using the softmax function as the activation function to represent a probabilistic distribution over the class labels. Since there are seven defined noise sources in this study, the output neurons of the last fully connected layer should be modified to seven for the audio CNN.

In order to train the audio CNN on the target audio data, transfer learning which is fine-tuning based on pre-trained AlexNet should be performed. The training process can be done by adjusting the weights of neurons using the backpropagation algorithm that is widely used for training the neural networks. As a result, by feeding the input variables with the size of $224 \times 224 \times 3$ into the network, the probability score of each noise source can be calculated as an output. By using this audio CNN, any noise source whose score is above the certain criteria can be suggested as the current noise source in the construction site.

2.4. Step 4. Noise source detection using the visual CNN

Based on the results of the noise classification in Step 3, the suggested noise sources should be detected on the video of the construction site. Since many activities of different types of construction equipment are operated at the same time on construction sites, it should be possible to detect multiple activities on a single image in real-time. Therefore, object detection algorithms that can automatically detect multiple objects in real-time are implemented for developing the visual CNN. In this study, an object detector algorithm called You Only Look Once v3 (YOLOv3), which is well-balanced in terms of speed and accuracy, is modified to be applied to the visual CNN (refer to Fig. 3) [23-25]. The YOLOv3 that uses the Darknet-53 which consists of 53 convolutional layers predicts the bounding boxes on the objects and the class confidence of the objects to localize and classify the objects. Further information about the architecture of the YOLOv3 can be found in [26]. By using multiple convolutional and residual layers, YOLOv3 can divide the input image with the size of 416×416 into grid cells with 3 different scales (i.e., 13×13 , 26×26 , and 52×52) to consider the various size of the object. Each grid cell has prediction results encoding 3 bounding boxes with different scales, objectness confidence representing the probability of the object existence on the grid cell, and class confidence representing the probability of belonging to each class. As a result, the dimension of the output for each grid can be represented as Eq. (2).

$$\text{Dimension}_{\text{output}} = S \times S \times (3 \times (4 + 1 + C)) \quad (2)$$

where S is the width and height of the grid, 3 is the number of bounding boxes, 4 is the properties of the bounding box which are bounding box coordinate, width, and height, 1 is the objectness confidence, and C is the class confidence for each class.

Since the YOLOv3 is for object detection rather than action detection, it needs to be modified to detect the activities of the construction equipment from the pre-processed visual data. Therefore, an early fusion which combines the data immediately on the first convolutional layer is applied to detect noise sources while preventing excessive calculations for the visual CNN so as to operate in real-time [27]. As such, the input dimension of the visual CNN should be modified from the YOLOv3 so as to coordinate with the dimension of the visual input data.

Just like the noise classification algorithm (i.e., audio CNN), transfer learning should be performed for the visual CNN based on the pre-trained YOLOv3. As a result, the construction equipment of the activity determined to be the noise source by the audio CNN can be localized on the real-time video as an output of the visual CNN.

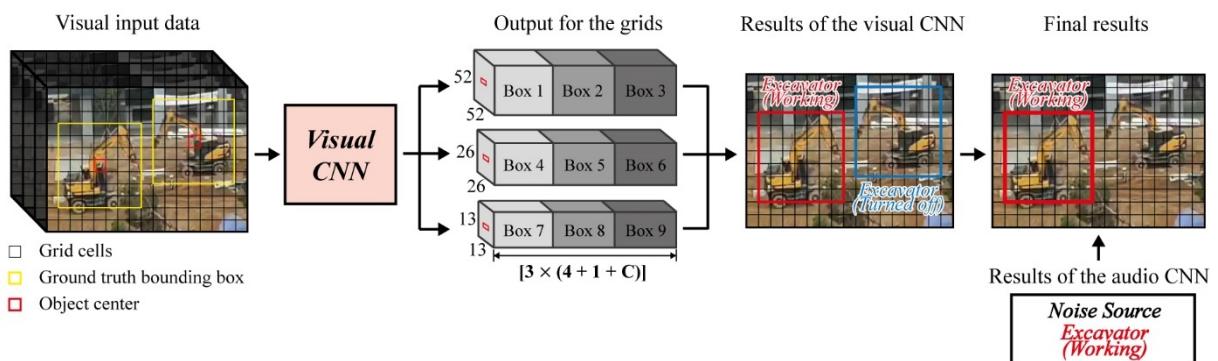


Figure 3. The process flow of the visual CNN

3. CONCLUSION

This study proposed a framework for an automated detection system of noise source on the whole construction site in real-time based on temporal audio and visual data using convolutional neural networks (CNNs). The proposed framework used the short-time Fourier transform (STFT) and temporal image processing to contain temporal features of the audio and visual data. In addition, the audio CNN and visual CNN were proposed with modifications of the AlexNet and the YOLOv3 in order to classify and detect the noise sources in real-time. The proposed framework could be helpful for environmental construction managers to efficiently identify the noise by automatically detecting the noise sources that

are generally complicated in the construction site due to many activities of various types of construction equipment. Furthermore, they can immediately control the noise level by providing information about the noise source in real-time that is essential to constantly and effectively reduce noise under a certain level. Thereby, complaints and conflicts between inhabitants and a construction company caused by construction noise can be effectively prevented. Moreover, noise-related health risks and productivity degradation of construction workers and inhabitants near the construction site can be minimized. With such contributions, the proposed framework could be applied to construction sites as a management system for securing the safety and productivity of the construction project.

However, this study only proposed a framework for the automated real-time detection system of noise sources in the construction site. Furthermore, some noise sources show various actions during a single working activity, such as digging and rotating for the excavator. Therefore, to effectively apply and validate the proposed framework, more detailed classes should be considered for developing the detection system along with the experimental study of the proposed framework with sufficient data.

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Real-time prediction on the slurry concentration of cutter suction dredgers using an ensemble learning algorithm

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Abstract: Cutter suction dredgers (CSDs) are widely used in various dredging constructions such as channel excavation, wharf construction, and reef construction. During a CSD construction, the main operation is to control the swing speed of cutter to keep the slurry concentration in a proper range. However, the slurry concentration cannot be monitored in real-time, i.e., there is a “time-lag effect” in the log of slurry concentration, making it difficult for operators to make the optimal decision on controlling. Concerning this issue, a solution scheme that using real-time monitored indicators to predict current slurry concentration is proposed in this research. The characteristics of the CSD monitoring data are first studied, and a set of preprocessing methods are presented. Then we put forward the concept of “index class” to select the important indices. Finally, an ensemble learning algorithm is set up to fit the relationship between the slurry concentration and the indices of the index classes. In the experiment, log data over seven days of a practical dredging construction is collected. For comparison, the Deep Neural Network (DNN), Long Short Time Memory (LSTM), Support Vector Machine (SVM), Random Forest (RF), Gradient Boosting Decision Tree (GBDT), and the Bayesian Ridge algorithm are tried. The results show that our method has the best performance with an R^2 of 0.886 and a mean square error (MSE) of 5.538. This research provides an effective way for real-time predicting the slurry concentration of CSDs and can help to improve the stationarity and production efficiency of dredging construction.

Keywords: Cutter suction dredger; Slurry concentration; Real-time prediction; Ensemble learning

1. INTRODUCTION

Dredging construction is the process of excavating and removing sediments and debris from below water level. The primary purposes of dredging include [1]: (1) to deepen the cross-section of channels to improve water transport capacity, flood discharge capacity, and irrigation capacity of the channels; (2) to deepen the cross-section of bays to meet the requirement of navigation, wharf construction, and ship docking; (3) to collect and bring up valuable substance from the bed of a river, sea, etc.; (4) to reclaim land from the sea.

Cutter suction dredgers (CSD) is one of the most widely used kinds of dredgers in dredging construction [2-4]. At present, most of the dredging constructions were completed with CSDs. The

reasons are: (1) compared with other kinds of dredgers (such as chain bucket dredger, drag suction dredger, grab dredger), the cost of using CSD is lower; (2) CSDs are suitable for various working conditions. Especially for the land reclamation constructions and dyke strengthening constructions, CSD is the only choice.

Because of the robust adaptability of CSD, researchers always pay much attention to CSD, no matter in academic and engineering. Tang and Wang [5] proposed an online fault diagnosis system for CSD. Ni et al. [6] studied the characteristics of CSD, simulated the construction process, and discussed the critical problems of CSD construction. Henriksen et al. [7] analyzed the underlying laws for soil disturbances exerted by cutter heads and proposed a near-field resuspension model. Zhang et al. [8] studied the flow law of the slurry in CSD slurry transportation systems based on numerical simulations. Li et al. [9] put forward a dynamic evaluation method on the efficiency of CSD constructions based on the real-time monitoring data.

There are various factors on CSD operation [10], such as the soil conditions and the performance of the dredger. Directly speaking, the CSD construction process is a controlling process to keep the slurry concentration within a proper range [11, 12]. However, because of the characteristics of the structure of the slurry transportation system, the slurry concentration cannot be measured in real-time, i.e., the monitoring data of the slurry concentration are time-lagged. Operators can only guess the current slurry concentration according to the time-lagged values and some other indices that can be measured in real-time, such as vacuum and swing speed. Obviously, this method is subjective and is not accurate. Although many studies have been done on the optimization of CSD operations, there is still not an effective and universal method to predict the slurry concentration with high accuracy. Miedema [13] designed an automatic control system to dynamically determine the boundary conditions of slurry flowrate based on mathematical derivation. Tang et al. [14, 15] presented an automation control system of CSD based on an expert system. Ye et al. [16] proposed a dredger cutter motor synchronous speed control system. Jiang et al. [17] studied the swing process of CSD and proposed to use an RBF-ARX model to optimize the swing process. Li et al. [18] presented a machine learning-based method to predict the construction productivity of CSD. However, even though the expert system proposed by Tang et al. [15] described how they predict the slurry concentration, however, Influencing factors (voltage and slurry concentration) considered in their research were not enough. Besides, most of the researches focuses on how other factors influence slurry concentration, but they still cannot solve the real-time measuring problem.

Real-time data prediction is research hotspot in intelligent construction, especially in the field of tunneling, excavation, earthwork, etc. Many key indicators can not be monitored in real time due to the variable geological conditions and complicated parameters of equipment. Data mining algorithms provide an effective solution for this problem [19-20]. For instance, Chen et al. [21] put forward a LSTM based method for predicting TBM parameters. Zhang et al. [22] presented a real-time analysis and regulation method for automatically steering Earth Pressure Balanced (EPB) based on Particle Swarm Optimization (PSO) and Random Forest (RF). Gao et al. [23] compared the performances of Long Short Time Memory (LSTM) neural network, recurrent neural network (RNN), gated recurrent unit (GRU), and some classical regression algorithms on predicting the parameters of TBM, and found that RNN-based predictors could usually make the best real-time predictions. Jing et al. [24] presented a TBM performance prediction model for limestone strata by establishing the relationship between penetration and normal force of single cutter. Gao et al. [25] used LSTM to predict tunnel boring machine (TBM) penetration rate. Leng et al. [26] developed a hybrid data mining method to predict TBM penetration rate based on convolutional neural network (CNN) and classification and regression tree (CART). From the perspective of construction, CSD dredging is similar to tunnel boring, and the fruitful progress of the real-time data prediction of TBM is a good reference for intelligent construction of CSDs.

In this paper, we proposed an ensemble learning-based method to establish the relationship between slurry concentration and some other indices that can be measured in real-time, and thus to predict the real-time slurry concentration of CSD dredging constructions. In the rest of the paper, the overall flow of the study is first presented. Then the construction technology of CSD is introduced. After that, the details of the methodology are described. Finally, a case study is conducted to test the method. Our methods, including the preprocessing, index selection, and the core algorithm, are tailored to the slurry concentration prediction problem. The results show that our algorithm is better than almost all the common regression algorithms, even including the Random Forest, the Deep Neural Network, and the Long Short Time Memory algorithm.

2. OVERALL FRAMEWORK

This flowchart of this research is as shown in Figure 1. First, the construction technology of CSD is briefly discussed in Section 3. Readers who familiar with it can skip this section. The preprocessing methods for the raw data are then proposed (see Section 4.1), including the processing method on the time-lag effect of slurry concentration, the rules for selecting normal construction data, and the filtering rules of the raw data. Among them, the solution to the time-lag effect is a standard method in dredging construction, but we will still talk about it briefly in the next section because it is crucial for the analysis. After that, the feature selection is proposed to find out the factors that both can be monitored in real-time and are related to slurry concentration (see Section 4.2). Then an ensemble learning algorithm is presented to establish the relationships between the selected indices and the slurry concentration (see Section 4.3). After that, a case study is carried out. In the case study, six advanced regression algorithms are used for comparison (see Section 5.2), including the Deep Neural Network (DNN), Long Short Time Memory (LSTM), Support Vector Machine (SVM), Random Forest (RF), Gradient Boosting Decision Tree (GBDT), and the Bayesian ridge algorithm. Finally, the research is ended with a meaningful discussion (see Section 5.3).

The red dashed rectangle in Figure 1 illustrates the main innovations of this research, including the data preprocessing method, the index selection method, and the proposed ensemble learning algorithm.

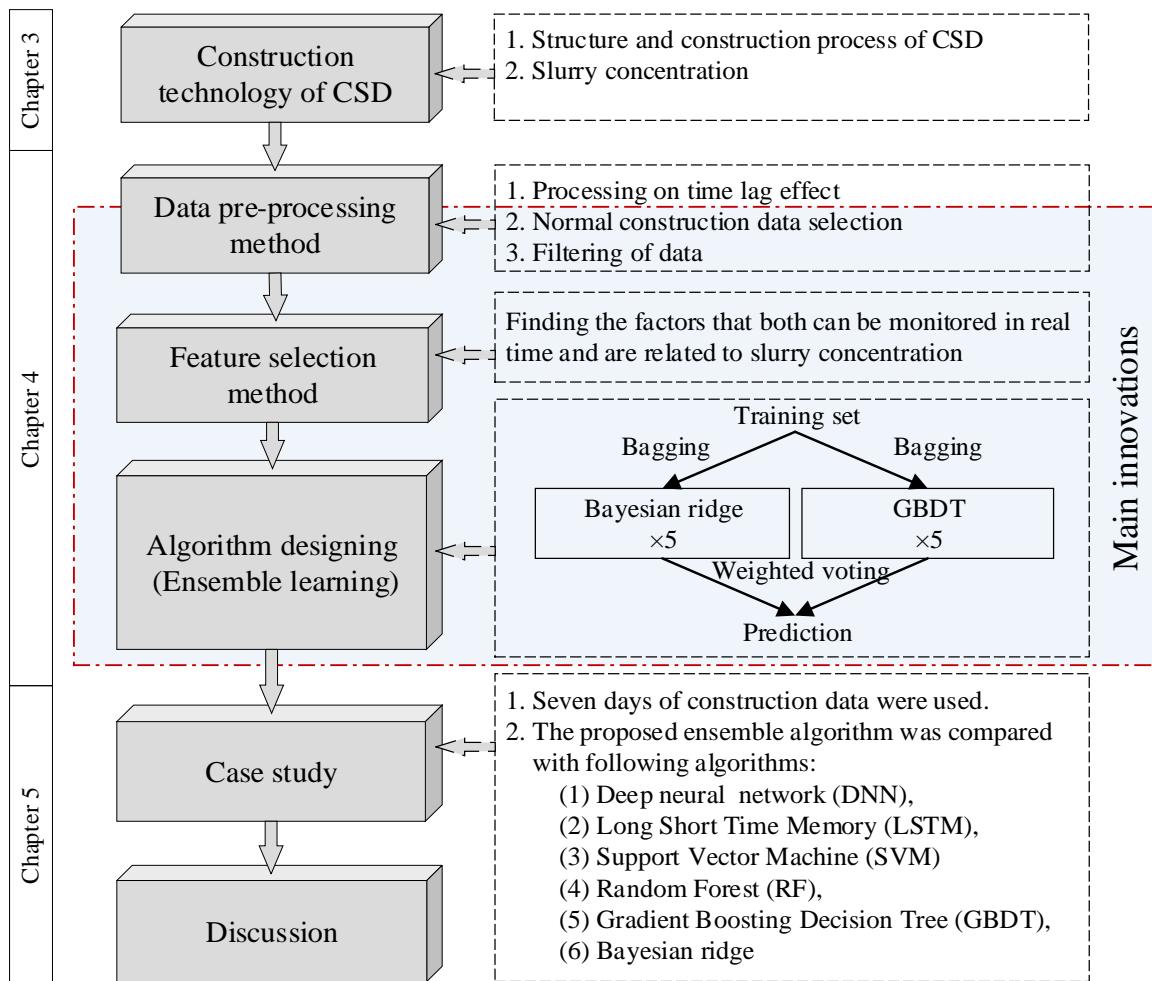


Figure 1. Flow chart of the research.

3. CONSTRUCTION TECHNOLOGY OF CSD

3.1. Structure and construction process of CSD

Figure 2 is the model of a typical CSD. The main components include a carriage, two spuds (primary spud and auxiliary spud), several pumps (underwater pump and carriage pumps), a ladder, two swing winches, two anchors, a cutter, and a series of pipelines. The primary spud (or working spud) is on the

carriage, and is used to fix the CSD; the auxiliary spud (or walking spud) is for assisting the primary spud in moving the CSD; the pumps are used to transport the slurry to a specific area through the discharge pipes, where the underwater pump is on the ladder, and the carriage pumps are in the carriage; the swing winches are for controlling the swing speed of the cutter; the cutter is on the end of the ladder, and is used to cut soil or rocks.

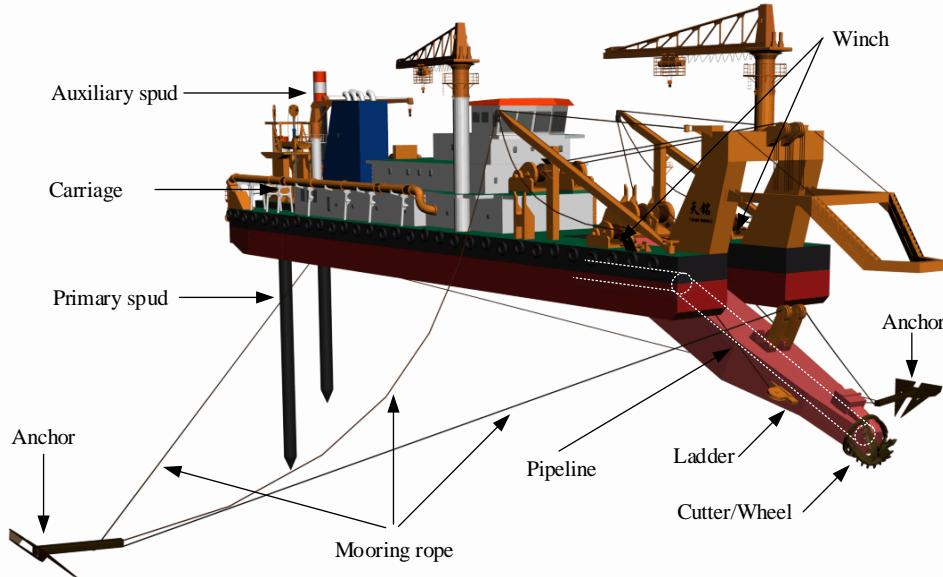


Figure 2. Structure of a CSD.

The construction process of CSD is as shown in Figure 3 and Figure 4. The first step is to fix the primary spud, and then retract or release the mooring ropes to make the cutter swing around the primary spud to dredge from one sideline of the channel to the opposite sideline. After that, the carriage will be moved forward for a step (a certain distance), and then by operating the mooring ropes and the ladder, the cutter will be swung to the reverse direction. The two swing processes can be regarded as a dredging cycle. After several cycles, the movement distance of the carriage will reach its limit, and then the whole CSD should be moved forward by shifting the spuds.

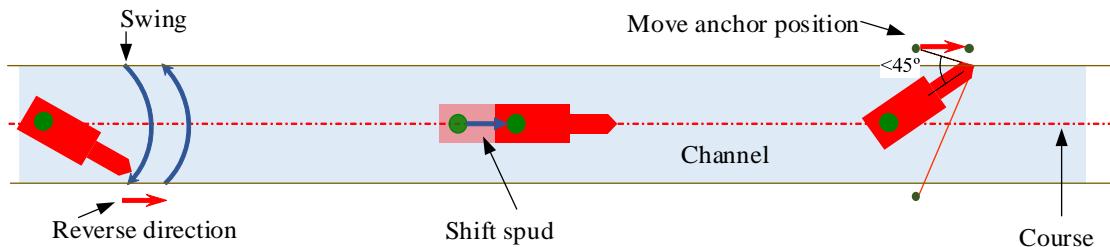


Figure 3. The construction process of CSD.

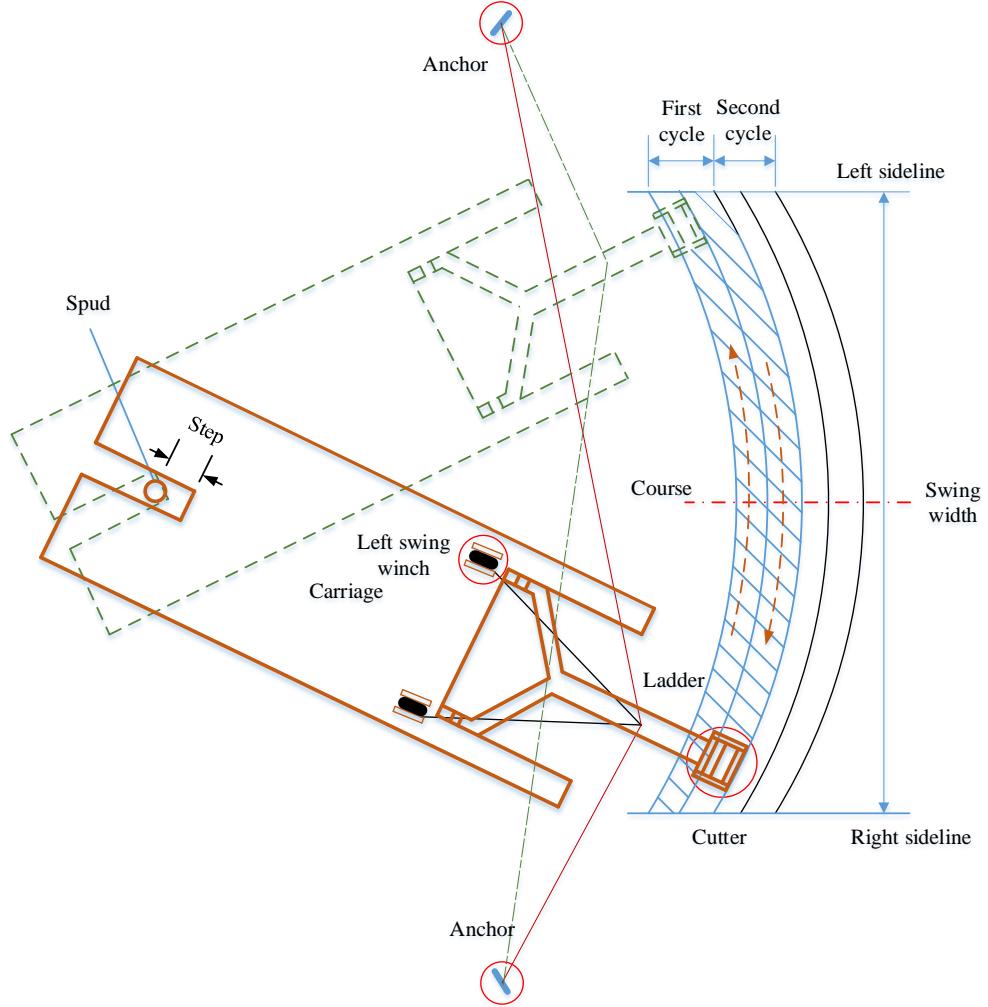


Figure 4. Swing process of CSD.

3.2. Slurry concentration

Slurry concentration is one of the most significant indicators in the dredging process [27]. As can be seen from Figure 3, the CSD is always in the swing process except shifting spuds. Therefore, swinging the cutter is the central part of CSD operations. So what is the major indicator for operators decide to accelerate or decelerate the swing speed? The answer is slurry concentration. An experienced operator can always keep the slurry concentration in a proper range by controlling swing speed. If the current slurry concentration is high, it will affect the normal operation of the devices (such as block the pipelines), and the swing speed should be slow down. On the other hand, if the current slurry concentration is low, the dredging productivity will be low, and usually, it's needed to accelerate the swing speed; but in some particular instances, low slurry concentration is caused by the soil conditions, for example, when dredging on a piece of rock, the slurry concentration will also be low, and some special measures will be needed. All in all, slurry concentration is the most important indicator of dredging.

However, during a swing process, it is impossible to obtain the real-time value of slurry concentrations because of the “time-lag effect”. As is shown in Figure 5, in the pipeline, the slurry first flows through the vacuum meter, and then the flow rate meter and the slurry concentration meter. Generally, the slurry concentration meter is dozens of meters far from the vacuum meter. Therefore, the values of the slurry concentration meter are not synchronized with the dredging process. The flowrate values are also not real-time, but they can be converted into real-time values with the continuity equation of flow. However, the time lag problem of slurry concentration cannot be easily solved. In the real construction process, operators always try to guess the current concentration according to the time-lagged values and some other indicators that can be obtained in real-time.

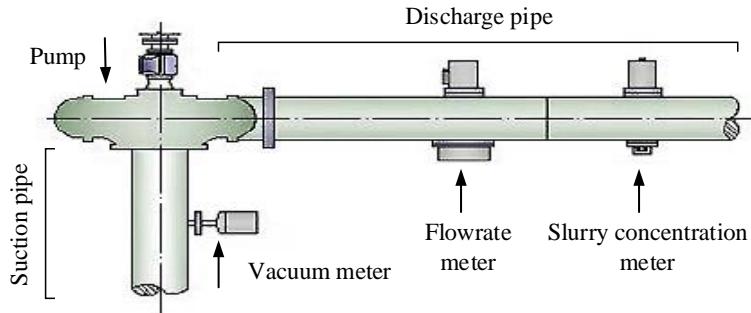


Figure 5. Schematic of time lag effect.

4. METHODOLOGY

4.1. Data preprocessing

4.1.1. Processing on time-lagged slurry concentration

The time lag effect, as mentioned in Section 3.2, is related to the distance between the vacuum meter and the slurry concentration meter. It is also related to the diameters of the suction pipe and discharge pipe, as well as the velocity of slurry. Generally, there are 10-30 seconds of lag. Only if time lag effect is eliminated we can establish the relationship between slurry concentration and other factors.

The time lag effect is eliminated with the continuity of flow [28]. The continuity of flow is defined as “the mean velocities at all cross-sections having equal areas are then equal, and if the areas are not equal, the velocities are inversely proportional to the areas of the respective cross-sections”, as shown in Figure 6. The continuity equation of flow is:

$$A_1 v_1 = A_2 v_2 \quad (1)$$

where A_1 is the area of the cross-section of the first pipe, v_1 is the flow rate in the first pipe; A_2 is the area of the cross-section of the second pipe, v_2 is the flow rate in the second pipe;

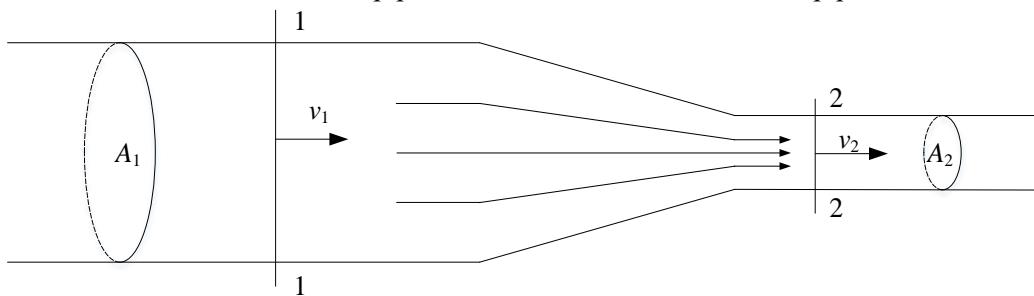


Figure 6. Schematic of the continuity of flow.

The integral of the slurry velocity over time is the distance that the slurry flows. Supposing that the diameter of the suction pipe is d_s and the diameter of the discharge pipe is d_d , the slurry velocity in the suction pipe is v_s , and the slurry velocity in the discharge pipe is v_d , then formula (2) can be derived according to the continuity equation of fluid.

$$v_s = \frac{d_d^2}{d_s^2} v_d \quad (2)$$

The d_s and d_d are constant, the v_s and v_d change over time, and the v_d can be monitored in real-time, as is shown in Figure 4. Supposing that the distance between the vacuum meter and the pump is l_s , and the distance between the slurry concentration meter and the pump is l_d , then the following equation set can be derived:

$$\begin{cases} \int_{t_0}^{t_1} v_s dt = l_s \\ \int_{t_1}^{t_2} v_d dt = l_d \end{cases} \quad (3)$$

where the l_s and l_d are constant. It can be seen that the slurry concentration at t_0 can be measured at t_2 .

Based on the above principle, the time lag effect of the slurry concentration can be eliminated.

4.1.2. Normal construction data selection

All the non-construction data should be removed. After eliminating the time lag effect, the period that the slurry concentrations are 0 can be determined as non-construction data. However, not all the periods that the slurry concentrations are not 0 belong to construction periods, and we definite that the dredging process begins at the first wave of slurry flow through the vacuum meter. Figure 7 shows how to determine the construction period in a construction cycle. The t_b and t_e represent the beginning and the ending of the slurry concentration series respectively, the t_{b-lag} and t_{e-lag} represent the beginning and the ending of the time-lagged slurry concentration respectively, and the construction period is from t_{b-lag} to t_e .

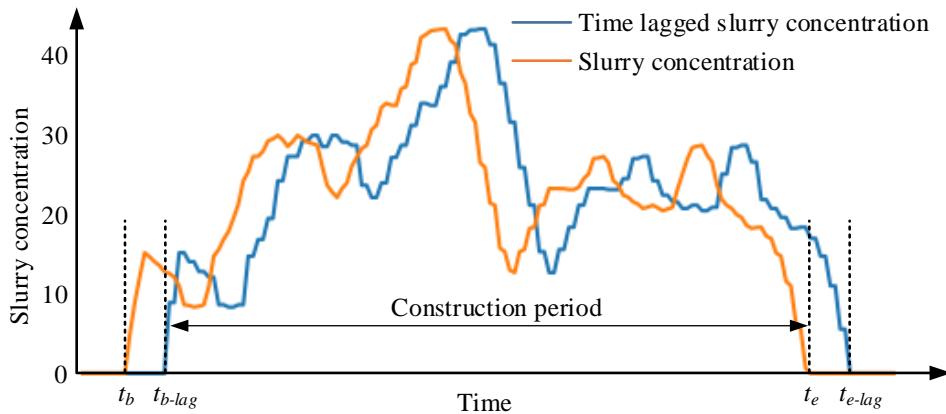


Figure 7. Construction data selection.

Besides, the abnormal data should also be removed: 1) some slurry concentration values may be extremely larger than others, and they should be removed because they may be caused by the sediment of the mud; 2) the electrical indices (such as the cutter motor power and winch power) contains a small amount of abnormal data, which should also be removed. In this research, the Box-plot was used to distinguish between normal and abnormal data.

4.1.3. Data filtering

In this research, three kinds of CSD were analyzed, and we found a common problem that even in the same CSD, the sampling frequencies of different indices are different. For example, the sampling frequency of the winch power meter is once every two seconds, while the sampling frequency of the vacuum meter is once every four seconds. However, the recording frequency of the whole monitoring system should be consistent with the maximum sampling frequency. Therefore, during the construction period, the records of the indicators with small sampling frequency will be copied several times to adapt the recording frequency, and it will lead to errors. One way to reduce these errors is to process the data with smooth filtering. Besides, some instruments are of low accuracy, filtering the data of them also helps for analysis. In this research, the Savitzky-Golay (S-G) filtering [29] was used.

The S-G filtering is commonly used in spectra pretreatment. Its main idea is to smooth a curve within a window by the polynomial fitting. Supposing that $X=(x_0, x_1, \dots, x_n)$ is the series that need to be filtered, then the i th point x_i will be smoothed as follows:

Supposing the length of the window is $l=2m+1$, and the power of the polynomial is $k-1$, then our goal is the fit the point series, $(x_{i-m}, x_{i-m+1}, \dots, x_i, \dots, x_{i+m-1}, x_{i+m})$, with the formula:

$$y = a_0 + a_1 x + a_2 x^2 + \dots + a_{k-1} x^{k-1} \quad (4)$$

The coefficients $(a_0, a_1, \dots, a_{k-1})$ are determined by the least square method. More details about this method can be found in the paper [28].

4.2. Index selection

The goal of this research is to establish the relationship between the slurry concentration and other indices; however, it is difficult to decide which indices should be used because there are hundreds of indices in CSD control system [30], as shown in Table 1. In this study, an index selection method is presented based on the working principles of CSD.

Table 1. Structure of the logging file of the CSD monitoring system

Time (2012-7-7)	1 Density (t/m ³)	2 Velocity (m/s)	3 Quantity of flow (m ³ /h)	4 Cutter power (kW)	...	713 Cutting angle (°)	715 Cutter head depth (m)
6:43:35	1.03	5.14	9304.35	936.55	...	2.04	17.8
6:43:37	1.03	5.15	9325.29	902.33	...	2.01	17.85
6:43:39	1.03	5.15	9325.29	902.33	...	2.01	17.85
6:43:41	1.04	5.19	9398.6	910.99	...	2.03	17.78
6:43:43	1.04	5.19	9398.6	910.99	...	2.03	17.78
6:43:45	1.04	5.19	9398.6	910.99	...	2.03	17.78
6:43:47	1.05	5.21	9435.25	893.03	...	2.03	17.78
6:43:49	1.05	5.21	9435.25	833.66	...	2.1	17.82

Figure 8 is a typical slurry transportation system of CSD. The dredging process can be simplified as (1) the winches control the swing speed of the cutter head, (2) the cutter head cut the soil into the slurry, and (3) the pumps then suck the slurry away. Therefore, swinging, cutting, and pumping are the three main processes of CSD construction and are the main factors of slurry concentration, and they are also the basis of the principle of the proposed index selection method.

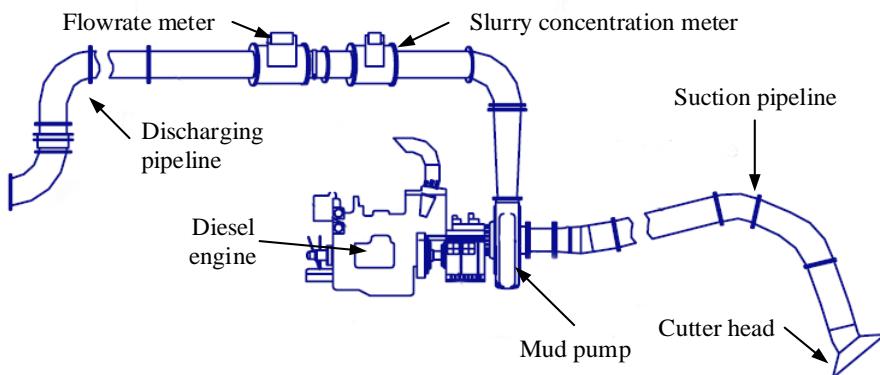


Figure 8. Slurry transportation system^[14].

Considering that the indices of different CSDs are not quite the same, we proposed to use “index class” to select indices. Four index classes are proposed: (1) swing-related indices, (2) cutter-related indices, (3) pump-related indices, and (4) time-lagged slurry concentration. Each class contains several indices, as shown in Table 2.

Table 2. Details of index class

Index class	Indices
Swing-related	Swing speed; Swing direction; Ladder angle
Cutter-related	Motor power; Cutting angle;
Pump-related	Vacuum; Drive power of shaft; Power; Rotate speed; Motor/Diesel power; Motor/Diesel speed
Time-lagged concentration	Time-lagged concentration

The reason why the time-lagged slurry concentration is selected is: although there is a delay in the concentration measuring, its value will not significantly larger or smaller than the real value. In the real construction process, the time-lagged value is still an essential reference to operators. It should also be noted that the numbers of the pumps of different CSDs are different, some CSDs only have one underwater pump, while some CSDs have one underwater pump and 1~2 carriage pumps, and all the pump-related indices of all the pumps are required for the slurry concentration prediction.

4.3. Ensemble learning

4.3.1. Structure of the algorithm

Ensemble learning [31-33] is to combine multiple meta-learners (algorithms) into a stronger learner by a particular strategy, as shown in Figure 9. The meta-learners can be any algorithms, such as Decision

Tree, Support Vector Machine, Artificial Neural Network, or even other ensemble learning algorithms. Lots of studies have shown that by combining the meta-learners together, an ensemble learning will have a performance than its meta-learners. These three key points to establishing an ensemble learning algorithm: (1) choosing the meta-learners, (2) determining the sampling strategy, and (3) determining the combining strategy.

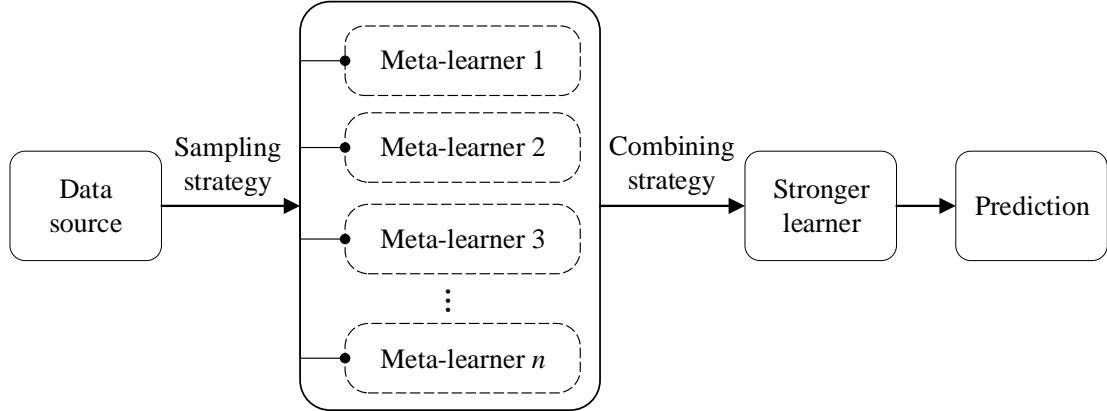


Figure 9. Structure of ensemble learning.

In this research, we used five Bayesian ridge learners and five Gradient Boosting Decision Tree (GBDT) learners as the meta-learners, and took Bagging as the sampling strategy, and used the weighted voting method as the combining strategy.

Bagging is the abbreviation of Bootstrap aggregating. According to the principle of Bagging, we train each meta-learner by random sampling from the training set with replacement. The numbers of samples in each random sampling are the same. After that, there will be ten well-trained learners. For a new sample, ten predictions will be made by the ten learners. The final prediction can be made by the formula:

$$p = \sum_{i=1}^n w_i p_i \quad (5)$$

where, p_i is the prediction of the i th meta-learner, w_i is the weight of the i th meta-learner, and p is the final prediction.

4.3.2. Meta-algorithm 1: Bayesian ridge

Bayesian ridge (BR) algorithm is a kind of Bayesian linear regression [34] and is based on the Bayesian inference. In the principle of Bayesian linear regression, the parameters of the linear model are regarded as random variables, and the posterior of the parameters can be calculated with prior knowledge. Supposing that $X = \{x_1, x_2, \dots, x_N\} \in \mathbf{R}^N$ and $y = \{y_1, y_2, \dots, y_N\}$ are the training set, then the Bayesian linear regression model is:

$$f(X) = X^T w, \quad y = f(X) + \varepsilon \quad (6)$$

where, w is the weights (or parameters), ε is the residual. It is assumed that the residual obeys the Normal distribution, and the variance of the residual obeys the Inverse-Gamma distribution:

$$\begin{cases} p(\varepsilon) = N(\varepsilon | \mu_n, \sigma_n^2) \\ \sigma_n^2 = \text{Inv-Gamma}(\sigma_n^2 | a, b) \end{cases} \quad (7)$$

where the mean of ε , μ_n , and the parameters, (a, b) , should be determined by the prior knowledge. Generally, the μ_n is set as 0.

Because the w is independent of X and σ_n^2 , the posterior of w can be derived formula (8) by the Bayes' theorem.

$$p(w | X, y, \sigma_n^2) = \frac{p(y | X, w, \sigma_n^2) p(w)}{p(y | X, \sigma_n^2)} \quad (8)$$

where, $p(y | X, w, \sigma_n^2)$ is the likelihood, and is determined by the linear regression model; $p(y | X, \sigma_n^2)$ is the marginal likelihood of y , and only related to the training set X . Our goal is to maximize the likelihood. Generally, there are three solutions, including the Maximum A Posterior estimation (MAP), conjugate prior method, and numerical method. In this research, the MAP is used, as

follows:

The prior knowledge is supposed:

$$p(\mathbf{w}) = N(\mathbf{w} | 0, \sigma_w^2) \quad (9)$$

Because the marginal likelihood is independent of \mathbf{w} , maximizing the posterior is equivalent to maximizing the product of the likelihood and the prior:

$$\arg \max_{\mathbf{w}} p(\mathbf{w} | \mathbf{X}, \mathbf{y}, \sigma_n^2) \Leftrightarrow \arg \max_{\mathbf{w}} p(\mathbf{y} | \mathbf{X}, \mathbf{w}, \sigma_n^2) p(\mathbf{w}) \quad (10)$$

Then the following formula can be derived:

$$\begin{aligned} \arg \max_{\mathbf{w}} p(\mathbf{y} | \mathbf{X}, \mathbf{w}, \sigma_n^2) p(\mathbf{w}) &\Leftrightarrow \arg \max_{\mathbf{w}} \log[p(\mathbf{y} | \mathbf{X}, \mathbf{w}, \sigma_n^2)] + \log[p(\mathbf{w})] \\ &= \log \left[\frac{1}{\sqrt{2\pi}\sigma_n} \exp \left(-\frac{\|\mathbf{y} - \mathbf{X}^T \mathbf{w}\|^2}{2\sigma_n^2} \right) \right] + \log \left[\frac{1}{\sqrt{2\pi}\sigma_w} \exp \left(-\frac{\|\mathbf{w}\|^2}{2\sigma_w^2} \right) \right] \quad (11) \\ &= -\frac{1}{2\sigma_n^2} (\mathbf{y} - \mathbf{X}^T \mathbf{w})^T (\mathbf{y} - \mathbf{X}^T \mathbf{w}) - \frac{1}{2\sigma_w^2} \mathbf{w}^T \mathbf{w} \\ &= -\frac{1}{2\sigma_n^2} \|\mathbf{y} - \mathbf{X}^T \mathbf{w}\|^2 - \frac{1}{2\sigma_w^2} \|\mathbf{w}\|^2 \end{aligned}$$

Because the coefficients of formula (11) are all negative, the maximization problem can be transformed into a minimization problem, and then the \mathbf{w} can be calculated, as follows:

$$\begin{aligned} \arg \min_{\mathbf{w}} \|\mathbf{y} - \mathbf{X}^T \mathbf{w}\|^2 + \lambda \|\mathbf{w}\|^2, \quad \lambda &= \frac{\sigma_n^2}{\sigma_w^2} \\ \Rightarrow \mathbf{w} &= (\mathbf{X}^T \mathbf{X} + \lambda \mathbf{I})^{-1} \mathbf{X}^T \mathbf{y} \end{aligned} \quad (12)$$

where, λ is the ratio of the variance of the residual and the variance of the weights, and can be calculated by the hyper-parameters; \mathbf{I} is a unit matrix.

4.3.3. Meta-algorithm 2: Gradient Boosting Decision Tree

Gradient Boosting Decision Tree (GBDT) itself is a kind of ensemble learning algorithm [35]. Its main idea is to respectively train its meta-learners (regression tree) in a stage-wise fashion. Supposing that the training set is $\mathcal{T} = \{(x_1, y_1), (x_2, y_2), \dots, (x_N, y_N)\}$, and the loss function is $L(y, f(x))$, then a GBDT model can be established with the following steps:

(1) Initialization. Calculate a value, c , that can minimize the loss function $L(y, c)$. The first regression tree can be determined:

$$f_0(x) = \arg \min_c \sum_{i=1}^N L(y_i, c) \quad (13)$$

(2) Supposing that M is the number of the regression trees, then the m th ($m=1, 2, \dots, M$) regression tree can be trained by step (3)~(6).

(3) For the i th training sample ($i=1, 2, \dots, N$), calculate the negative gradient of the loss function of the current (the $(m-1)$ th) regression tree:

$$r_{mi} = - \left[\frac{\partial L(y_i, f(x_i))}{\partial f(x_i)} \right]_{f(x)=f_{m-1}(x)} \quad (14)$$

(4) Make a new dataset, $\{(x_1, r_{m1}), (x_2, r_{m2}), \dots, (x_N, r_{mN})\}$, then use this dataset to determine the R_{mj} ($j=1, 2, \dots, J$). R_{mj} is the range of the leaf nodes of the m th regression tree, and J is the number of the leaf nodes.

(5) Calculate the c_{mj} that can minimize the loss function. This step is similar to step (1).

$$c_{mj} = \arg \min_c \sum_{x_i \in R_{mj}} L(y_i, f_{m-1}(x_i) + c) \quad (15)$$

(6) Update the $f(x)$:

$$f_m(x) = f_{m-1}(x) + \sum_{j=1}^J c_{mj} I(x \in R_{mj}) \quad (16)$$

(7) The final GBDT model can be described:

$$F(x) = \sum_{m=1}^M \sum_{j=1}^J c_{mj} I(x \in R_{mj}) \quad (17)$$

4.4. Algorithms for comparison

In related researches such as the prediction works of TBM parameters [21-26], algorithms such as RF, LSTM, SVM are usually used. In this research, six representative algorithms, including DNN, LSTM, SVM, RF, and GBDT, are tested for comparison.

(1) Deep Neural Network (DNN). DNN is attracting more and more attention in recent years and has been proven to have a tremendous non-linear mapping ability [36, 37]. Compared with traditional Artificial Neural Network (ANN), DNN has more hidden layers and more complex structures. In this study, we designed a DNN with eight hidden layers, as shown in Figure 10.

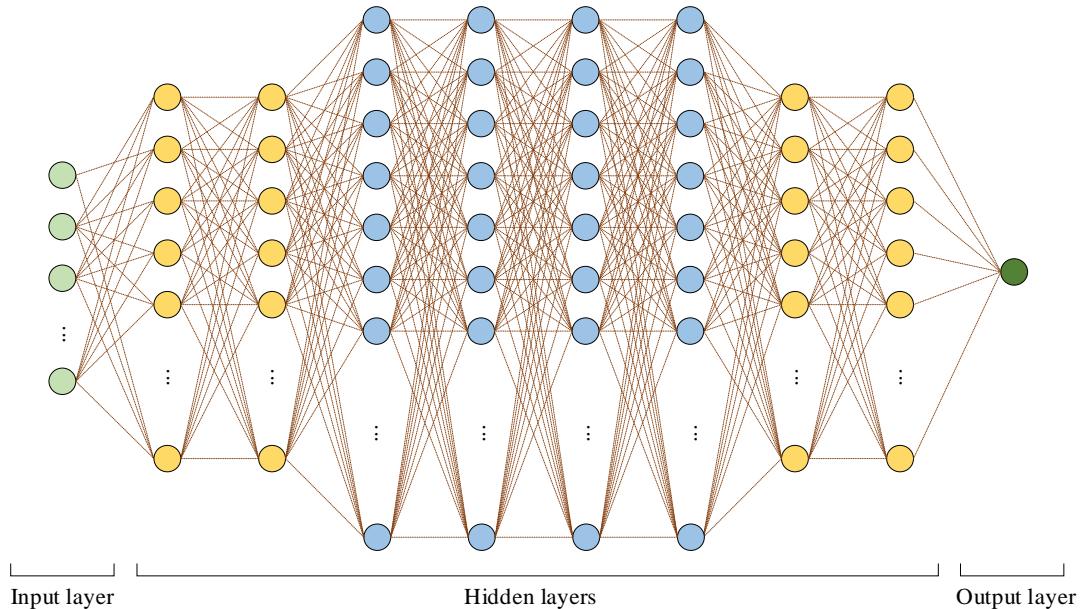


Figure 10. Structure of the DNN.

In the DNN model, the input layer were the indices shown in Table 2, and the output was the slurry concentration. The numbers of the neural cells in each hidden layers were 100, 100, 200, 200, 200, 200, 100, 100. We used the Relu function as the activation function. The learning rate is 0.003.

(2) Long Short Time Memory (LSTM). LSTM is a kind of recurrent neural network (RNN) and is good at solving time sequence problems [38, 39]. A typical LSTM model is shown in Figure 11.

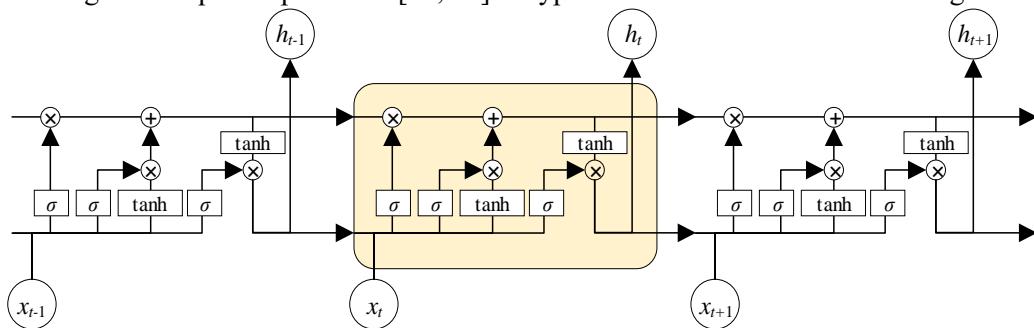


Figure 11. Structure of LSTM.

In this research, we designed an LSTM model with two hidden layers, and each hidden layer contained 50 cells. The time step was five. The learning rate was 0.0001. The batch size was 64. The number of epoch was 100.

(3-6) Support Vector Machine (SVM), Random Forest (RF), GBDT, and Bayesian ridge. SVM and RF are two of the most widely used algorithms, so they are not repeated here. The details of them can be found in the two publications [40, 41]. The GBDT and the Bayesian ridge algorithm have been described in Section 4.3

4.5. Evaluation methods

To quantitatively evaluate the performances of the algorithms, two evaluation indices were used in this study.

(1) Goodness of fit (R^2). The R^2 is calculated:

$$R^2 = \frac{\left(\sum_{i=1}^n (y_i - \bar{y})(\hat{y}_i - \bar{y}') \right)^2}{\sum_{i=1}^n (y_i - \bar{y})^2 \sum_{i=1}^n (\hat{y}_i - \bar{y}')^2} \quad (18)$$

(2) Mean square error (MSE). The MSE is calculated:

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2 \quad (19)$$

where, n is the number of samples, y_i is the target of the i th sample and \hat{y}_i is the prediction of the i th sample.

5. CASE STUDY

5.1. Data collection

Totally seven days' CSD monitoring data were collected from a dredging construction of Tianjin, China. The sampling frequency of the monitoring system was once every two seconds. In total, there were 112,637 samples. Figure 12 shows the slurry concentrations of the CSD at different dredging positions in the dredging area.

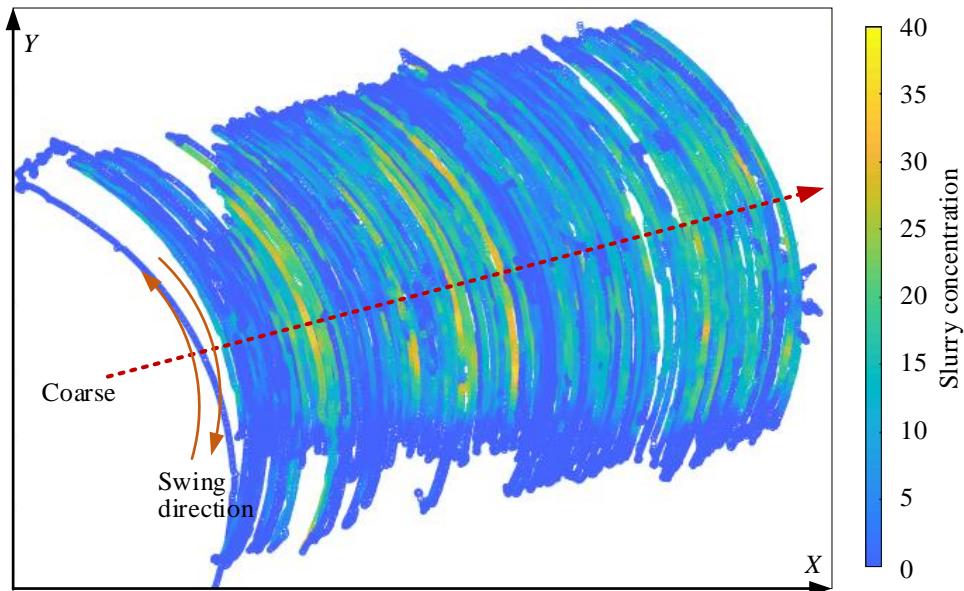


Figure 12. Distribution of the slurry concentration in the dredging area.

The control system of the CSD can be simplified as Figure 13, and 715 indices were monitored. Compared with the typical slurry transportation system, this CSD had three pumps, including an underwater pump and two carriage pumps. According to the proposed index selection method (Table 2), 23 indices were selected, including two swing-related indices, two cutter-related indices, 18 pump-related indices, and the time-lagged slurry concentration. It should be noted that the “ladder angle” was not selected because the data quality of this index was poor.

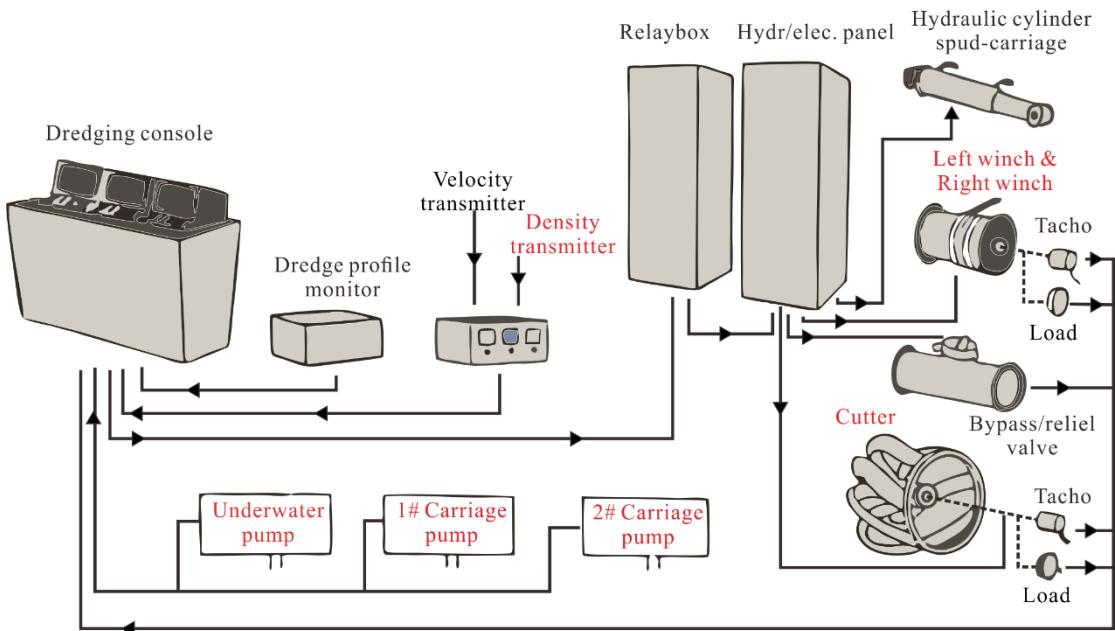


Figure 13. Control system of the CSD.

5.2. Experimental results

The time lag effect of the slurry concentration was first eliminated using the method of Section 4.1.1, as shown in Figure 14. For a further explanation, the vacuum data are also plotted in Figure 14. It can be seen that the real slurry concentration changes in sync with the vacuum. When the vacuum decrease, more mud will be sucked into the pipeline, so the slurry concentration will increase – and vice versa.

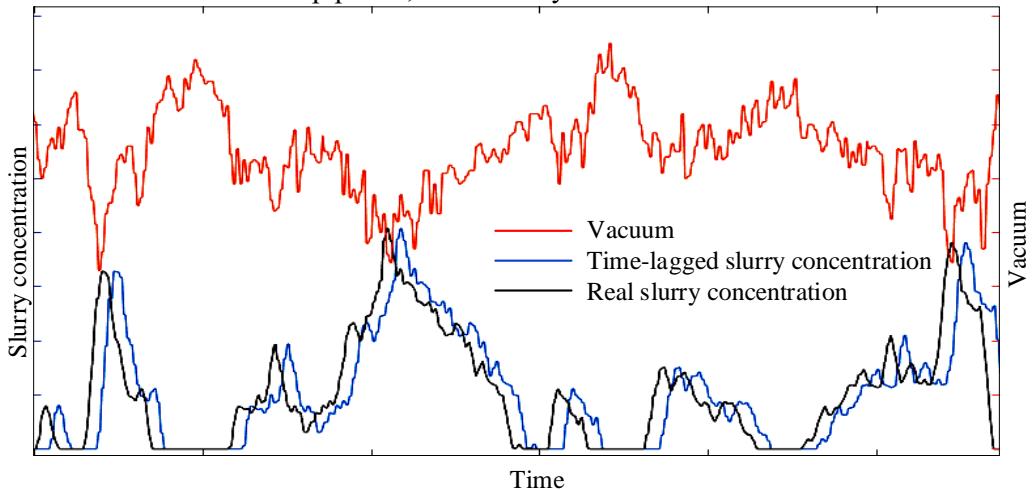


Figure 14. Comparison between the time-lagged slurry concentration and the real values.

All the normal construction data were then selected using the method proposed in Section 4.1.2. After that, the data of seven indices were filtered using the method proposed in Section 4.1.3, including the vacuum of the underwater pump, the drive power of the shaft of the underwater pump, the rotate speed of the underwater pump, the motor speed of the underwater pump, the motor power of the underwater pump, the cut angle, and the time-lagged slurry concentration. Figure 15 shows the raw data and the filtered data of the vacuum of the underwater pump.

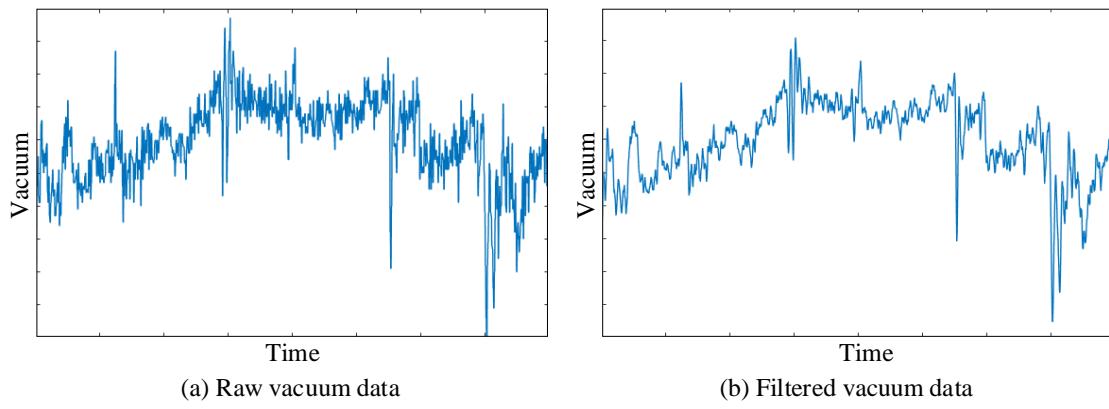


Figure 15. Example of data filtering.

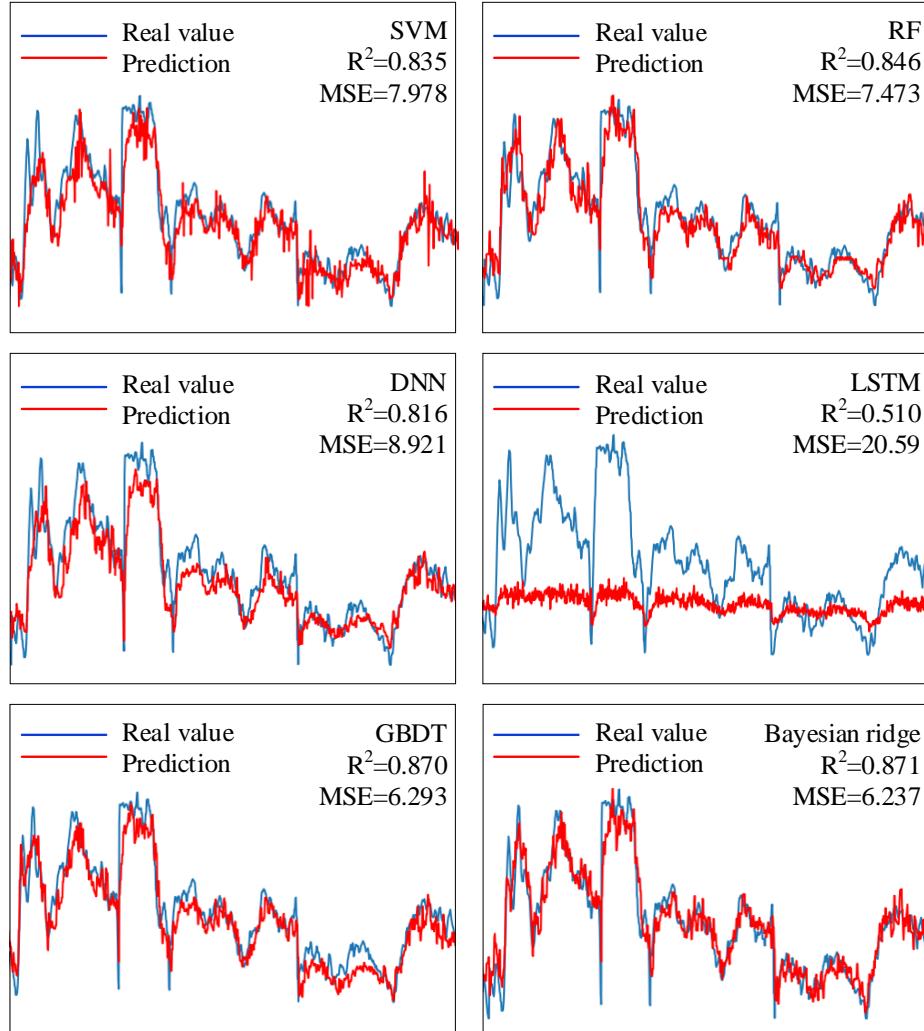


Figure 16. Results of SVM, RF, DNN, LSTM, GBDT, and BR (the plots just shows a part of the result).

After data preprocessing, we used the proposed ensemble learning algorithm and another six algorithms to establish the relationship between the slurry concentration and the selected 23 indices. Three days' data were used to train the algorithms, and the last four days' data were used to test them. A part of the test results is shown in Figure 16-17. The details of the predictions results of all the tested algorithms are listed in Table 3.

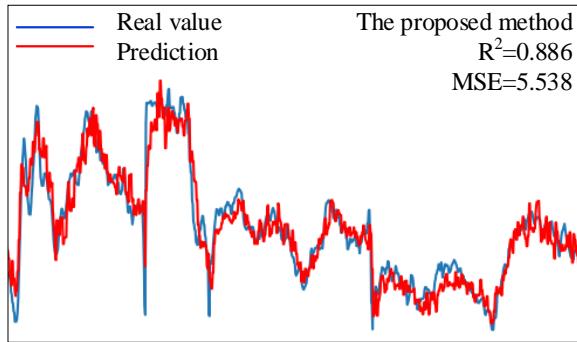


Figure 17. Result of the proposed ensemble learning algorithm (the plots just shows a part of the result).

Table 3. Structure of the logging file of the CSD monitoring system

	SVM	RF	DNN	LSTM	GBDT	BR	The proposed method
R ²	0.835	0.846	0.816	0.510	0.870	0.871	0.886
MSE	7.987	7.473	8.921	20.56	6.293	6.237	5.538

5.3. Discussion

5.3.1. About the selection of meta-learner

Although it seems from the plots that the RF, GBDT, and Bayesian ridge can also fit the data well, the R² and MSE show that the proposed ensemble learning algorithm is significantly better than the other algorithms. DNN and LSTM have the worst performances. Actually, at the beginning, DNN was the first choice for the study because the problem was complex and the number of data was large enough, and is thought to have the best performance as long as the network was well-designed and the parameters were suitable. However, numerous trials showed that DNN was not suitable for this task, and its performance was even not as good as SVM and RF. Meanwhile, the linear regression algorithms, such as Bayesian ridge and logistic regression, were found to have good effects, although their principles were not complicated at all.

This discovery made us realize that the relationship between the slurry concentration and the other selected indices should be closer to a linear relationship than a non-linear relationship. Therefore, when designing the ensemble learning algorithm, half of the meta-learners were set as the Bayesian ridge algorithms to specially learn the linear part of the relationship, and finally, it produced the best results.

5.3.2. About the index class

At the end of the research, we studied the importance of the four index class proposed. Figure 18 shows the MSEs when the indices of one of a certain index class were not used. It can be seen that the time-lagged slurry concentration has the most significant importance, and the MSE will be three times as large as the best result if this index is not used. The Pump-related indices also have a significant effect on the regression.

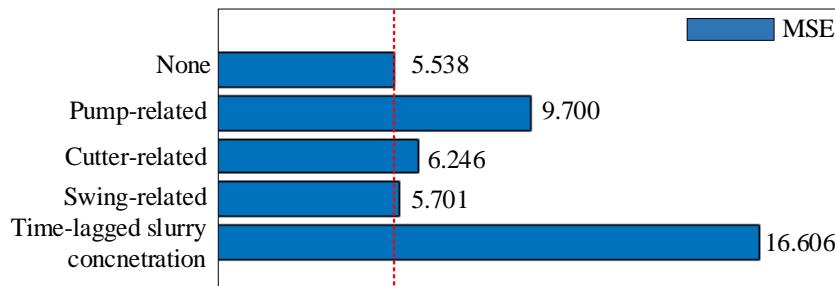


Figure 18. Important analysis of index classes.

Furtherly, the variance inflation factor (VIF) was used to check the multicollinearity among the indices, and the indices with low VIF values (<10) are listed in Table 4. After that, we just used the six

listed indices to test the predictive effect, and the R^2 is 0.839, 5% lower than the best result, 0.886; the MSE is 7.80, 40% higher than the best result, 5.538. Such a result indicates: (1) there is at least one key index in every index class, i.e., swing direction in the swing-related class, motor power in the cutter-related class, vacuum in the pump-related class, diesel speed in the pump-related class, and time-lagged concentration; (2) low VIF indices may not have bigger impacts on the prediction than high VIF indices, e.g., the swing-direction has the lowest VIF value (Table 3), while the swing-related index class contributes the least among the four classes (Figure 18); (3) according to the R^2 and MSE, although the other indices are with high VIF values, they are important to improve the predictive effect, meaning that the proposed algorithm is effective in extracting valuable information from different indices even if the indices have high multicollinearity with others.

Table 4. Indices with low VIF values (<10)

Index	Class	VIF
Swing direction	Swing-related	1.06
Motor power	Cutter-related	5.33
Vacuum (underwater pump)	Pump-related	2.31
Diesel speed (1# Carriage pump)	Pump-related	2.41
Diesel speed (2# Carriage pump)	Pump-related	4.48
Time-lagged concentration	Time-lagged concentration	7.75

Index selection is one of the most challenging problems in this study because of the large number of the indices. Moreover, different CSDs have different indices, so the indices that appropriate for the slurry prediction of one CSD may not exist in another CSD. Therefore, we suggest taking the proposed “index class” as a reference to select indices. Actually, another case study was also carried out in the experiment to test the proposed method further. The data were collected from another CSD, and the indices of this CSD were less than the CSD in the first case. Totally 11 indices were then selected according to Table 2. Figure 19 shows that the proposed method works well, as shown in. However, the result is worse than in the first case. It mainly because the number of indices was less, and the number of data was not enough (less than one days’ data). Overall, this method are with general applicability.

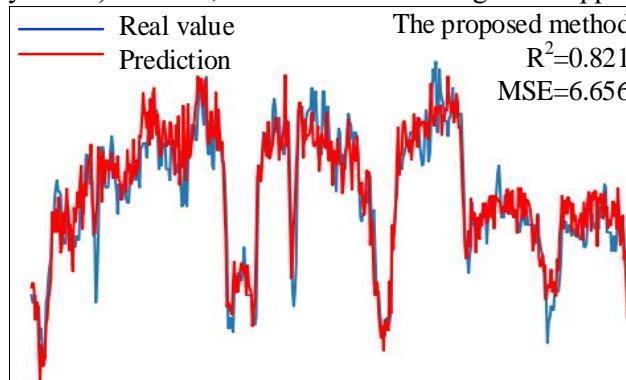


Figure 19. Results of another case study.

5.3.3. About data filtering

Filtering is a standard method in signal analysis. In most instances, data filtering is helpful for analysis. However, the poignant matter needs to be aware of is whether or not data filtering is appropriate. In this research, we think that it depends on the roles of the data: the training set can be filtered, while the test set cannot be filtered. Training data are used to establish the algorithm, and they are the given data. However, the test set is the unknown data, and they should be regarded as the real-time data of a real construction process. For the S-G filter, the value of a point is modified according to the points before and after it. But during a construction process, it is impossible to get a series of future value to filter the current value. In our research, all the data of the test set were not preprocessed, as shown in Figure 20.

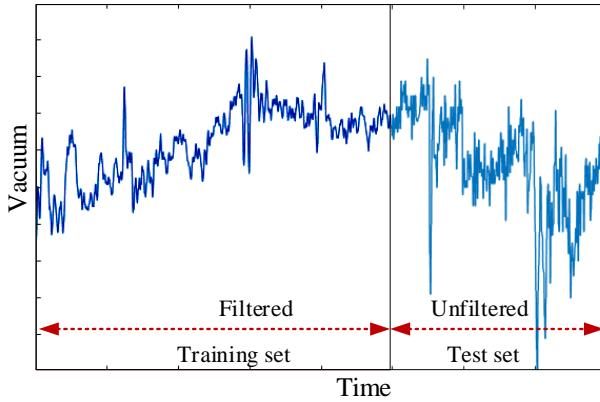


Figure 20. Illustration of which data can be filtered.

There is also a kind of method named real-time filterings, such as the Forward Linear Prediction (FLP) and the Kalman Filter. However, the FLP needs a control function, and the Kalman Filter needs a covariance matrix, both of which are not easy to be determined, and more works are needed to test the applicability of them on the research.

6. CONCLUSION

In this research, an ensemble learning-based method is proposed to predict the real-time slurry concentration of CSD dredging construction. There are three main innovations: at first, the preprocessing method for the CSD monitoring data is proposed; then we put forward the concept of “index class” to select the important indices; after that, an ensemble learning algorithm is presented to fit the relationship between the slurry concentration and the indices of the index classes. The results show that the proposed method is effective. The R^2 and MSE of the ensemble learning algorithm are 0.886 and 5.538, respectively. Such a fitting effect is better than almost all the commonly used regression algorithms, even including the DNN and LSTM. Besides, our method is with general applicability. We also test our method with the data of another CSD, as discussed in Section 5.3.2. It shows that the R^2 can reach to 0.82 and the MSE is less than 7, even though there are only several hours’ data for training. Some important conclusions are also drawn from the research: (1) linear regression meta-models play an important role in the proposed algorithm; (2) the pump-related indices are the most significant indices except for the time-lagged slurry concentration; (3) the proposed algorithm is universal for different types of CSDs.

In conclusion, the proposed method can help the CSD operators to obtain the slurry concentration immediately; thus, it can help to improve the stationarity and production efficiency of dredging construction.

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XX. SUSTAINABILITY CONSTRUCTION AND MANAGEMENT IV (G2)

A Decision Support Model for Intelligent Facility Management through the Digital Transformation

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Abstract: Information on the energy consumption of buildings that can be obtained through conventional methods is limited. Therefore, this study aims to develop a model that can support decision making about building facility management through digital transformation technologies. Through the IoT sensor, the building's energy data and indoor air quality data are collected, and the monitored data is visualized through the ELK Stack and produced as a dashboard. In addition, the target building is photographed with a 360-degree camera and maps using a tool to create a 360-degree tour. Using such digital transformation technologies, users of buildings can obtain various information in real time without visiting buildings directly. This can lead to changes in actions or actions for building management, supporting facility management decisions, and consequently reducing building energy consumption.

Key words: digital transformation, facility management, 3d digital twin, building energy performance, indoor environmental quality, real-time monitoring and diagnostics

1. INTRODUCTION

1.1. Background and Objectives

There have been various plans to reduce the CO² emissions globally to address the global warming issue, which is due to the continuous rise in the CO² concentration in the earth's atmosphere. Based on the primary energy consumption level, South Korea is the eighth country in the world with the largest primary energy consumption. As South Korea does not produce energy sources like oil, the energy-saving efforts of the government or civil movements are more important [1]. According to the Fourth Report by Intergovernmental Panel on Climate Change (IPCC), 40% of the global energy consumption is from buildings [2]. Additionally, a 2007 survey by Internal Energy Agency (IEA) showed that building energy consumption accounts for 25% of the total annual energy consumption in South Korea. The energy consumption in buildings is closely linked to the building occupants, whose behaviors are extremely difficult to monitor and control. In particular, as the information about the building energy consumption that can be offered to the building occupants is extremely limited, it is difficult to convince them to save energy. An energy bill is a well-known example of such information offered to the building occupants, but it has limitations. First, it shows the energy costs one month after they are incurred, and as such, it cannot offer the building occupants real-time information on their energy consumption. Also, it does not provide detailed information on energy consumption(e.g., information by space, equipment, or time of day), thus not allowing the energy consumption pattern to be identified. Finally, it does not

offer information on the indoor environmental quality (IEQ) and cannot obtain information on the sustainability of the space and the degree of comfort of the building occupants.

To address these limitations, it is necessary to conduct a study on the development of a system that can monitor in real time the information on the building energy consumption by equipment and IEQ, based on which the energy efficiency and IEQ by space can be diagnosed. Therefore, this study aimed to develop a decision-making model that could support intelligent facility management through digital transformation. Towards this end, it aimed to realize the digital transformation through the following two approaches: (i) software-based digital transformation; and (ii) hardware-based digital transformation. Software-based digital transformation involves monitoring and diagnosing real-time data (energy efficiency and IEQ) through IoT-based sensors, whose results are then visualized and produced as dashboards. Hardware-based digital transformation, on the other hand, is to take panoramic images with a 360° camera and produce a 360° tour model. By integrating and applying these digital transformation technologies, the proposed decision-making model allows building occupants to verify real-time information on energy efficiency and IEQ per space remotely, without visiting the actual space. Furthermore, by using the information offered through the digital transformation, the proposed model can offer building occupants a comfortable and sustainable space and encourage changes in the occupants' energy-saving behavior.

1.2. Scope and Methodology

This study established as its spatial scope Sangju Wonkwang Preschool located in Sangju, Gyeongsangbuk-do, South Korea <Fig. 1>. The building consists of a three-story main building and a two-story annex. On the first floor are a teachers' room and two classrooms, and on the second and third floors are a learning preparation room and three other classrooms.



Figure 1. Sangju wonkwang kindergarten (main building)

The real-time data collected with Internet of Things (IoT)-based sensors (energy and indoor environmental sensors) were used to realize dashboards with which to monitor and diagnose the energy efficiency and IEQ per space in real time. Furthermore, a 360° camera was used to take panoramic images, based on which a 360° tour model was produced. The duration of this project was from September 2018 to June 2019, and the data collected during this period were used in the study.

2. THEORETICAL OVERVIEW

2.1. Preliminary Survey

Digital transformation is the application of digital technologies like cloud computing, IoT, big-data solutions, and artificial intelligence (AI) to the existing societal structure, and the innovation of the overall services and operational processes in the society as a result. Digital transformation in the construction industry can be examined through two general approaches. The first is the software-based

approach, in which the various data generated in the lifecycle of a building are digitized. The occupants' location and behavioral information, energy efficiency, and IEQ information per space, and other data generated in the maintenance stage of a building, are collected and analyzed in real time to establish an intelligent facility management system. The second is the hardware-based approach, in which the external elements of a building, like the site arrangement, building structure, and indoor finishing, are digitized. Often called "3D digital twin," this approach is widely used for various purposes in South Korea and abroad. Mainly applied in the design stage, this 3D digital twin method is less often applied in the maintenance or disposal stages [3]. The cases in South Korea where it was applied in the maintenance stage are POSCO's "Smart Factor System" and SK Telecom's "3D In-building Facility Management System," among others.

POSCO's Smart Factor System used a real-time big-data analysis method to analyze the quality factor defect elements based on the facility conditions. This system applied an "active alarm" to rotation and exchange items to improve the accuracy of the quality factor defect elements offered in real time.

On the other hand, SK Telecom's 3D In-building Facility Management System was realized for the establishment of a communication facility maintenance guidance system for VIP customer facilities, with the aim of reducing the repair time in the case of communication issues. With this system, the maintenance workers can easily identify the locations and statuses of communication facilities as well as the locations and network systems of the related facilities based on the 3D digital twin technology.

2.2. Real-Time Dashboard Realization Technology

2.2.1. IoT-based Sensor

The realization of dashboards requires the monitoring and diagnosis of real-time data. This study used two IoT-based sensors for real-time data collection: (i) Enertalk; and (ii) Awair <Fig. 2>. Enertalk collects energy information like the power consumption of a building by space and equipment to present the hours of usage of facilities and equipments as well as the standby power consumption, electricity consumption pattern, and power consumption by appliance. Awair, on the other hand, is an indoor environmental sensor. It collects information on the temperature, humidity, CO₂ concentration, chemicals, and ultrafine dirt per space, and digitizes and expresses each index.



Figure 2. Types of sensors

IoT-based sensors are connected via a communication network like WiFi, and the collected data are sent to a server in real time. As such, the collected data can be monitored and diagnosed in real time.

2.2.2. ELK Stack

ELK Stack, a system that analyses data in various formats from diverse resources, is key to the realization of a dashboard. As an open-source system offered by Elasticsearch, ELK Stack includes various software programs, and the first letters of the three most popular programs, Elasticsearch, Logstash, and Kibana, were used to name it "ELK." Elasticsearch is an open-source search and analysis engine that supports the search, analysis, and storage of data; Logstash is a data collection pipeline, and Kibana is an extensible UI tool with which to visualize data and construct and manage all the functionalities of ELK Stack. Using each of these functions, the user can realize a dashboard that can visualize the results of the real-time data monitoring, diagnosis, and analysis.

2.3. 3D Digital Twin Realization Technology

2.3.1. 3D Digital Twin

Digital twin can be defined as an object that contains a series of virtual information models and data [4][5], or as a technology or means, like a simulation [6]. Generally, it can be defined as a digital profile of the past or present status of a physical object or process. In addition, different definitions can be used based on the functions in various fields [7]. In the construction industry, 3D digital twin means “the digitized data of the images or drawings of a site or building.” Different from the existing computer-based design, it is significantly more than mere digitized data [8]. Models based on the 3D digital twin technology allow for swift and simple extension and connection with IoT technologies. Therefore, it can lead to the best business results as it is repeatedly adjusted to make it adapt to environmental or operational changes [9].

The core of the 3D digital twin technology is to realize a site or building in 3D. As it is limited to realizing 3D data in conventional images, 3D digital twin uses panoramic images with a wider angle of view. Thus, the best method of acquiring the data required for the 3D digital twin is using a 360° camera <Fig. 3>.



Figure 3. 360° camera

2.3.2. 360° Camera

Unlike the conventional cameras, a 360° camera offers wider vertical and horizontal angles of view. Thus, it can offer spherical panoramic images with only the two lenses attached to the front and back parts of the camera, which are called “360 panorama.”. While a 360° panorama can be realized with the images taken by a conventional camera, it is not suitable for use as the resulting image can cause considerable distortion in the 3D image stitching process.

A 360° panorama can offer better reality and immersion to a site or building than the conventional images. Thus, it can be used to help improve the building occupants’ understanding of the space.

2.3.3. 360° Tour Model

A 360° panorama taken by a 360° camera can be used to restructure a 360° tour model, and this study used Cupix’s tool for this purpose [10]. The information that can be expressed by individual panoramas is limited because it does not offer spatial continuity. To address this limitation, Cupix’s tool can be used to convert the 360° panorama to a 360° tour model. When consecutive 360° panoramas are uploaded to the tool, a road-view-like format can be produced in the order of the images. By revising the result, a 360° tour model can be constructed. Such a 360° tour model can improve the building occupants’ understanding of the space and can make the usage of the dashboard more intuitive.

3. RESEARCH FRAMEWORK

3.1. Installation of IoT-based Sensors

First, an energy sensor and an indoor environmental sensor were installed in the target building to collect, monitor, and diagnose real-time data. In this study, energy and indoor environmental sensors were installed in eight classrooms in Sangju Wonkwang Preschool, and the data collected from such sensors were used. The normal operation of the installed sensors can be confirmed by each application of sensors.

3.2. Production of the Real-Time Dashboard

A dashboard was created with ELK Stack to visualize the data monitored from the IoT-based sensors. In this process, the sensors should always be connected to a communication network, and the real-time data should be sent to a server. ELK Stack should immediately visualize the incoming real-time data. The real-time dashboard produced as such offers energy efficiency and IEQ information by space and equipment in various formats.

3.3. Imaging of 3D Panoramas

A 360° camera should be used to take pictures of the target building. Before taking pictures, the characteristics of the space should be determined in advance, and the image shooting should consider these characteristics. For an indoor space that is relatively small and has many variables, images should be taken with smaller gaps. More care should be taken to take pictures of doors that separate two different spaces because if the shooting gap is too wide, the spatial characteristics cannot be sufficiently detected by Cupix's tool, halting the mapping process. If in an outdoor space, there are fewer obstacles and more marked signals (trees, buildings, etc.) than in an indoor space so that pictures can be taken with wider gaps than those of indoor images, thus reducing the shooting time.

Sangju Wonkwang Preschool, the target building of this study, has similar-looking spaces arranged in repetition; as such, pictures were taken with smaller gaps. Based on an arbitrary point in the shooting area, pictures were taken by moving zigzag at fixed distances (indoor: 1-2 m; outdoor: 3-4 m), without any missing area so that a natural-looking panorama tour could be created. The zigzag shooting method is more useful than the spiral shooting method for mapping purposes.

In this way, images of all the spaces, from the first to the third floor of the main building, were taken, and a sufficient number of 3D panoramas were acquired.

3.4. Production of the 3D Digital Twin

The panoramas are uploaded to Cupix's tool by setting the name of the file as well as the number of sections, selecting and uploading files, and confirming such files. Among these processes, the setting of the number of sections can be used when the target area is wide or when the target area consists of several spaces (e.g., Room 1, Room 2, and Bathroom). Once the desired number of sections is entered, each section name can be determined <Fig. 4>, and the panoramas suitable for each section can be uploaded.

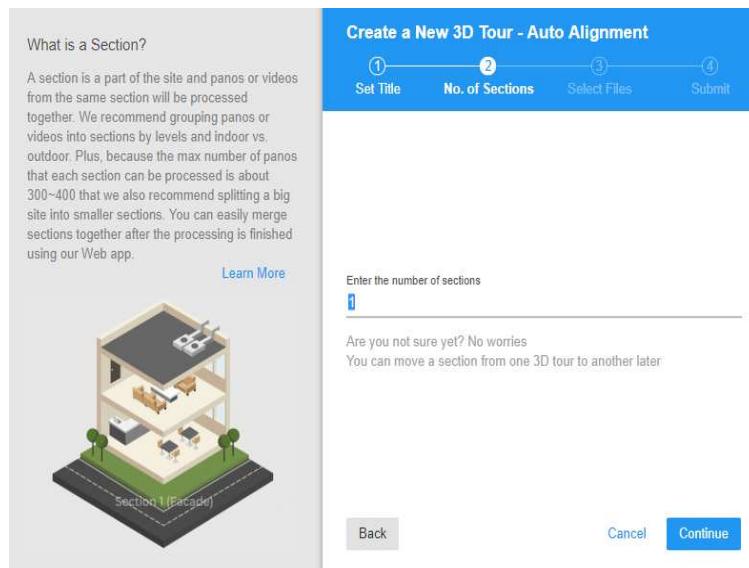


Figure 4. Setting up sections within the Cupix tool

As has been explained, Sangju Wonkwang Preschool consists of similar-looking spaces allocated repeatedly. Therefore, the section was divided into the first floor, the second floor, and the third floor of the main building, and was uploaded as such. While the main building has three floors, the panoramic point is expressed on a plane; as such, the panoramas at each floor may become tangled, making it impossible to distinguish one from another. Furthermore, if some panoramas are not identified during

the mapping, the other panoramas can also be affected, and all the panoramas may end up failing to express spatial information. Therefore, the section should be further divided to reduce such risks.

Once the uploading is completed, more detailed editing processes, such as the setting of the coordinate axes, the setting of the floor level, and the selection of unused panoramas, can be performed in the editing stage. Here, unused panoramas do not express spatial characteristics, and therefore, even if they are entered to the section manually, the coordinates, viewpoint, height, etc. should also be manually determined. It is crucial to shoot images with suitable gaps so as to not generate any unused panorama. While taking images with a 360° camera, personal information, including portrait rights, can be unintentionally included in the images. People's faces are automatically detected and blurred by Cupix's tool, but other personal information, like the license plate of a car, should be identified and processed carefully. Once all these editing processes are completed, a 360° tour model is produced to realize an actual 3D digital twin, which can then be used by the building occupants to browse through the target space anytime and anywhere.

3.5. Synchronization of the 3D Digital Twin and the Dashboard

For the synchronization of the 3D digital twin and the dashboard, the “pin” function in the tour editing stage of the mapping process is used. The pin function allows texts or external video links to be added in the space so as to help present information that cannot be expressed with the 360° tour model. Through the use of this function, the dashboard produced by ELK Stack can be expressed in the 360° tour model. This improves the user's understanding of the space and helps identify the energy efficiency and IEQ information clearly. Shown in Fig. 5 is an example of the spatial characteristics using the pin function of Cupix's tool.

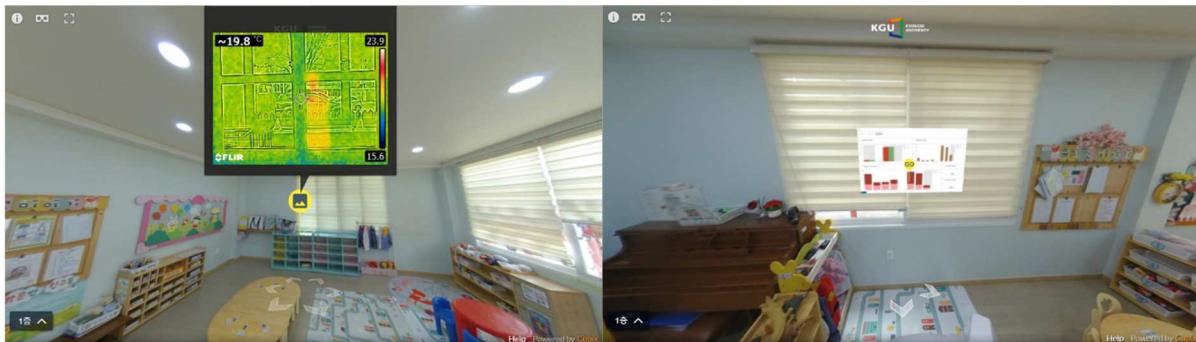


Figure 5. Example of using Pin functions

4. RESULTS

4.1. Realization of the Real-Time Dashboard

This study aimed to realize a real-time monitoring and diagnosis system of the information of a space (energy efficiency and IEQ) so as to support the building occupants' decision-making on the degree of spatial comfort and sustainability. A dashboard was created to offer real-time data on the energy efficiency and IEQ data of each space of the target building, Sangju Wonkwang Preschool. Using this dashboard, the users can check the statistical analysis results and graphs on the energy consumption of the target space by equipment, the energy consumption pattern by the time of day, and the recommended standard and comfort level by IEQ index, without physically visiting the space <Fig. 6>.

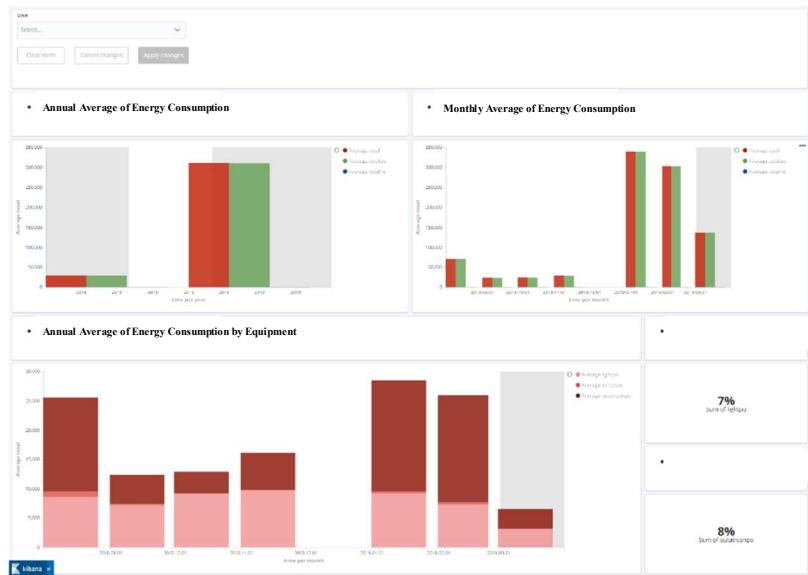


Figure 6. Example of Energy Consumption Dashboard

4.2. Realization of the 3D Digital Twin

The target building was divided into a total of three sections (the first, second, and third floors of the main building), and a 360° camera was used to take images of each section 1-2 m apart, to create 360° panoramas. These panoramas were uploaded to Cupix's tool and were mapped by spatial continuity to create a 3D digital twin. Using the pin function of Cupix's tool, the 3D digital twin was linked to the dashboard. In this way, the structure and characteristics of the actual space were identified remotely, and at the same time, the energy efficiency and IEQ information of the space could be analyzed.

4.3. Applications and Expectations

4.3.1. Remote diagnosis

In the past, building or facility occupants had to visit the site in person or seek help from energy measurement specialists to acquire data on their energy consumption. Also, most of the data were superficial data offered by energy statements or energy consumption bills, and the same can be said of the IEQ information. By using the model (particularly the real-time dashboard) developed in this study, however, real-time data that used to be difficult to acquire could now be collected, and also, additional data from various points of view can be simply verified by adjusting the parameters of ELK Stack

4.3.2. Acquisition of the information of a space

. It is relatively easy for the building occupants to understand the building information by space (energy efficiency and IEQ) because they possess some background knowledge of the space and information. Those who are neither occupants nor facility managers, however, usually lack understanding of the space and information, and it is difficult for them to make an informed decision based on simple data. Using the model developed in this study (and particularly 3D digital twin), their level of visual understanding of the space and information can be improved.

4.3.3. Link to BIM

Further analysis of the space is possible by using tools like Cupix. In other words, besides the spatial shape, information on the lengths and thicknesses of the walls, although somewhat limited, can be acquired. If such technology continues to be developed, it can be linked to BIM and used for the maintenance of a building [11].

5. CONCLUSION

In this study, a decision-making model was developed for supporting intelligent facility management through digital transformation. The spatial scope of the study was Sangju Wonkwang Preschool in Sangju, Gyeongsangbuk-do, South Korea, and the duration of the study was from September 2018 to

June 2019. First, a dashboard that would offer the real-time monitoring and diagnosis results of the building energy efficiency and indoor environmental quality (IEQ) was developed. Also, the panorama images from a 360° camera were mapped to produce a 360° tour model. By integrating these two outputs, a 3D digital twin model was created. In this way, the study established a framework based on which building occupants could verify and take action on the energy efficiency and IEQ information of the target space remotely, without physically visiting the space.

In the existing method, the data on the energy consumption of a building or facility and the IEQ per space are very limited. As a result, there is extremely insufficient evidence based on which the building occupants or facility manager could take action. Using the proposed intelligent facility management system, however, the building occupants or facility manager could use the various data (monitoring and diagnosis results) shown on the dashboard as the bases for their decision. Furthermore, it is expected to reduce the facility maintenance costs considering that with the proposed system, the building occupants or facility manager would not have to physically visit the site to obtain the information that they need. In the future, it is expected that a framework with which to consider facility management in advance in the integrated process, from the planning stage to the design, construction, and maintenance stages of a building, will be established by linking the proposed system to BIM.

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Dynamic Sustainability Assessment of Road Projects

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Abstract: Traditionally, road projects are initiated based on an assessment of their economic benefit, after which the environmental, social and governance effects are addressed discretely for the project according to a set of predetermined alternatives. Sustainable road infrastructure planning is vital as issues like diminishing access to road construction supplies, water scarcity, Greenhouse Gas emissions, road-related fatalities and congestion pricing etc., have imposed severe economic, social, and environmental damages to the society. In the process of addressing these sustainability factors in the operational phase of the project, the dynamics of these factors are generally ignored. This paper argues that effective delivery of sustainable roads should consider such dynamics and highlights how different aspects of sustainability have the potential to affect project sustainability. The paper initially presents the different sustainability-assessment tools that have been developed to determine the sustainability performance of road projects and discuss the inability of these tools to model the interrelationships among sustainability-related factors. The paper then argues the need for a new assessment framework that facilitates modelling these dynamics at the macro-level (system level) and helping policymakers for sustainable infrastructure planning through evaluating regulatory policies.

Keywords: Sustainability performance, Dynamic factors, Sustainability-assessment framework.

1. INTRODUCTION

The construction and operation of public-infrastructure assets can have a significant effect on society and the region [1]. The United Nations (UN) Secretary-General Antonio Guterres emphasised the importance of the sustainability of infrastructure projects during the UN Climate Change Conference of Parties (2018): ‘Infrastructure investment will be crucial. The world should adopt a simple rule; if big infrastructure projects are not green (sustainable), they should not be given the green light. Otherwise, we will be locked into bad choices for decades to come’ [2]. According to Infrastructure Australia (IA), the broad concept of sustainability lies in the simultaneous concretisation of the quadruple bottom line of sustainability aspects (i.e., social, environmental, economic and governance) [3]. A sustainability-assessment framework helps to incorporate such sustainability aspects of a project into the design, construction and operation of infrastructure assets [1]. The early decades of the twenty-first century are seeking a change in focus on environmental reporting in road agencies [4] because the conventional assessment processes and procedures for infrastructure projects do not necessarily measure the qualitative and quantitative effectiveness of all aspects of sustainability-related to the project [1]. This need for change in the focus of environmental reporting has arisen because of the existence of an agglomeration of sustainability-assessment frameworks, all of which have different purposes, reporting requirements, and outcomes [3].

It is known that different types of road networks and traffic conditions change the dynamic properties of the overall road system performance. In the absence of such detailed field studies in this area, simulation modelling becomes necessary to improve knowledge and understanding of different road design parameters, traffic characteristics, innovative methods utilised and how it affects criteria of sustainability aspects over time (social, environmental, economic and governance).

This paper does not aim to assess whether current assessment tools for infrastructure sustainability are valid and useful. Instead, the specific objectives of this paper are first to provide a comparative review of the different tools and methods used for infrastructure-sustainability assessment, and later to provide a comprehensive overview of the best methods that can be used to measure sustainability performance'. By considering the limitations addressed in the comparative review, a conceptual framework is proposed by utilising the extensive literature review to fill the identified research gap. As roads typically have a design life of 20 to 40 years, the level of consideration of future trends analysing the performance of roads related to environmental impacts, economic risks, and social movements will have a significant impact on their long-term benefits. The following section presents a list of the sustainability-assessment frameworks, principally focusing on comparing frameworks that are used in the roads sector.

2. LITERATURE REVIEW

2.1 Sustainability-assessment Methods for Road Agencies

Sustainability-performance assessment is a methodology 'that can help decision-makers and policy-makers decide what actions they should take and should not take in an attempt to make society or project more sustainable' [5]. In 2012, the International Federation of Consulting Engineers classified these assessment tools into four categories based on their origin and utility (see Figure 1) [6]. Therefore, when considering the sustainability of the project, the significant methods to be followed by the road agencies are first, the decision-support tool of the projects, and second, the rating of the project performance against an industry benchmark.

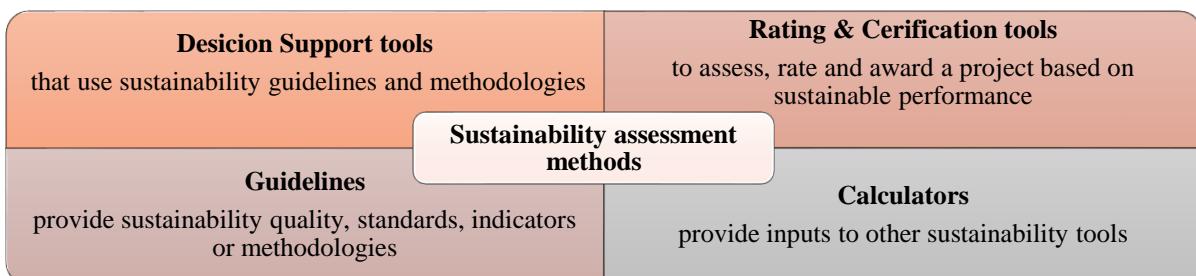


Figure 1. Categories of Sustainability-assessment Tools [6]

Measuring the sustainability performance of an infrastructure project using any of these assessment methods requires applying either qualitative or quantitative criteria or indicators for each of the sustainability aspect [7]. The Global Reporting Initiative (GRI), a non-profit organisation provides offers with a comprehensive list of criteria and indicators to apply when measuring sustainability performance using such assessment tools. The GRI also provides comprehensive guidelines on the type of sustainability information [3].

2.1.1 Decision-support tools

Decision making about public-infrastructure investment is often complicated [8]. While appraising of public works, broader regional environmental factors incorporating political and social domains are important to consider while considering the sustainability assessment [9]. A holistic decision-making framework must capture the decision-making system comprising rules, processes, and outcomes that

are framed within a broader context composed of organisational factors and boundaries [9]. The International Federation of Consulting Engineers (2012) has characterised various models as ‘decision-support tools’, and guarantees that these tools are being appraised by systems that utilise multicriteria analysis methods to survey sustainability performance [8]. The most prominently used decision-support tools from the literature review apart from the cost-benefit analysis are presented in Table 1.

Table 1. Tools for Sustainability Decision Support [10]

Tool	Certifying body	Sector	Country
ASPIRE	ARUP	Infrastructure	UK
HalSTAR	Halcrow	Infrastructure	UK
INDUS	Mott MacDonald	Infrastructure	UK
SPeAR	ARUP	Infrastructure	UK
Scottish Transport (STAG)	Transport Scotland	Transport	Scotland

2.1.2 Rating tools/schemes

Numerous sustainability-rating schemes have been launched in the infrastructure sector since the release of the BREEAM rating Scheme, United Kingdom (UK), has led to the development of sustainability assessment. These rating schemes are developed based on different criteria and corresponding credit points that address various dimensions of sustainability [1]. Each of the credits is assigned with a score based on the weighting given to the criteria [1]. Current available existing rating tools and schemes relevant to roads and infrastructure projects are presented in Table 2.

To categorise the criteria of each tool, the present research used Infrastructure Sustainability Council of Australia (ISCA) as a guide because the ISCA manual provides information on which criteria support which of the quadruple bottom lines. While Table 3 presents the percentage of categories based on the ratio of total points for the criteria under each sustainability category to the total points available for the sustainability-assessment tool under consideration. The overall percentage for some of the assessment tools is less than 100% because of the rounding of values. Other rating tools such as INVEST and BE²ST in Highways were omitted in Table 3 because of the lack of information on their point system.

Each assessment tool presented in Table 2 had in common specific criteria aiming to achieve the four aspects of sustainability (social, economic, environment and governance) in road projects. The weight placed on various aspects of sustainability varied among the different tools. These tools are useful in situations where a project team does not wish to allocate a budget for third-party sustainability evaluation. In such a case, the project team can use one of the self-evaluation tools based on the requirements and focus of the project. The analysis presented in Table 3 shows the percentage of the weight given to each quadruple bottom line in the selected assessment tools.

Comparative analysis utilising Table 3 reveals that the number of indicators assigned to a category in the infrastructure-sustainability-assessment tools is not directly proportional to the significance of the sustainability aspects (i.e., credit/weight). Figure 2 provides the percentage of weights for each aspect under the sustainability-rating tools in the form of bar charts. For example, while in the ISCA Rating Tool, 35% of the total number of indicators is related to the environmental dimension, the points assigned to these sets of indicators sum up to only 27.2% of the total points. Likewise, 29% of the total number of indicators are related to the governance dimension, whereas the score assigned to these sets of indicators sums up to 34.4% of the total points. Further, the different emphasis has been given to different indicators in different tools, as revealed in Table 3. It is evident most of the tools assign greater significance/weightage to resource management related criteria (e.g., energy, water, resources, and materials).

Table 2. Existing rating tools and schemes relevant to road projects [3]

Sustainability-performance and sustainability-rating tools	Road specific	Decision-support tools			Rating tools and/or schemes			Calculators			Guidelines		
		P, D	C	O, M	P, D	C	O, M	P, D	C	O, M	P, D	C	O, M
IS Rating Tool by Infrastructure Sustainability Council of Australia (ISCA)		✓	✓	✓	✓	✓	✓						
INVEST (Integrated VicRoads Environmental Sustainability Tool): rating tool	YES				✓	✓	✓						
Carbon Gauge Calculator	YES							✓	✓	✓			
I-LAST (Illinois Livable and Sustainable Transportation)	YES				✓	✓							
Bottom Line ² software											✓		
CEEQUAL					✓	✓							
Envision		✓	✓	✓	✓	✓	✓						
GreenLITES	YES	✓	✓	✓									
Greenhouse Gas Calculator	YES							✓	✓				
eTool Life Cycle Assessment software													
BE ² ST in Highways	YES	✓	✓										

Note: P, D = planning and design; C = construction; O, M = operation and maintenance

When the conventional criteria of rating tools and road engineers' perspectives on sustainability road are compared (i.e., after qualitative and quantitative analysis), it is clear that the following considerations of sustainability are the foremost and most common considerations in making road projects sustainable [11]:

1. safety and health: reducing public-property damage and severe and fatal injuries
2. economic development: enhancing the goals and objectives of a project, working with economic development agencies, monitoring sustainable outcomes
3. energy and materials: reducing waste by recycling and reusing materials and reducing energy consumption by using energy-efficient fixtures and renewable energy to protect limited natural resources

4. pollution: reducing air or noise pollution from construction equipment and materials
5. resilience: designing road projects to ensure they have the flexibility to handle future hazards and climate change.

Table 3. Common Categories and Their Indicators Included in Sustainability Assessment Tools

Rating Tools		ISCA		Envision		CEEQUAL		GreenLITES		Greenroads		I-LAST	
Dimensions	Categories	Credit/Weight	Categories	Credit/Weight	Categories	Credit/Weight	Categories	Credit/Weight	Categories	Credit/Weight	Categories	Credit/Weight	
Environment	Energy	9.27	Materials	17	Land use and ecology	600	Water Quality	20	Environment & Water	10	Environment	51	
	Green Infrastructure	3.54	Energy	15	Landscape and historic environment	450	Material & Resources	66	Material & Design	6	Water Quality	36	
	Pollution	1.45	Water	9	Resources	1450	Energy & Atmosphere	104			Lighting	16	
	Materials and resource recovery	5.99	Siting	7	Pollution	400	Sustainable Sites	81			Materials	43	
	Water	6.54	Conservation	16							Design	27	
	Ecology	4.54	Ecology	7									
Economic			Emission	16									
	Business case	14.51	Economy	10									
	Benefits realisation	4.54											
Social	Stakeholder engagement	9.08	well being	9	Transport	400			Access & Livability (AL)	10	Transportation	42	
	Legacy	4.36	Mobility	2	Communities and Stakeholders	550			Utilities & Controls	8			
	Heritage	2.18	Community	5					Construction Activities	11			
	Workforce	9.08											
Governance	Culture & context	3.87	Resilience	40	Resilience	600	Innovation	7	Creativity & Effort	4	Planning	19	
	Leadership	9.08	Collaboration	10	Management	550			Project Requirements	12	Innovation	6	
	Sustainable Procurement	11.34	Planning	12									
	Resilience	5.32											
	Innovation	10											

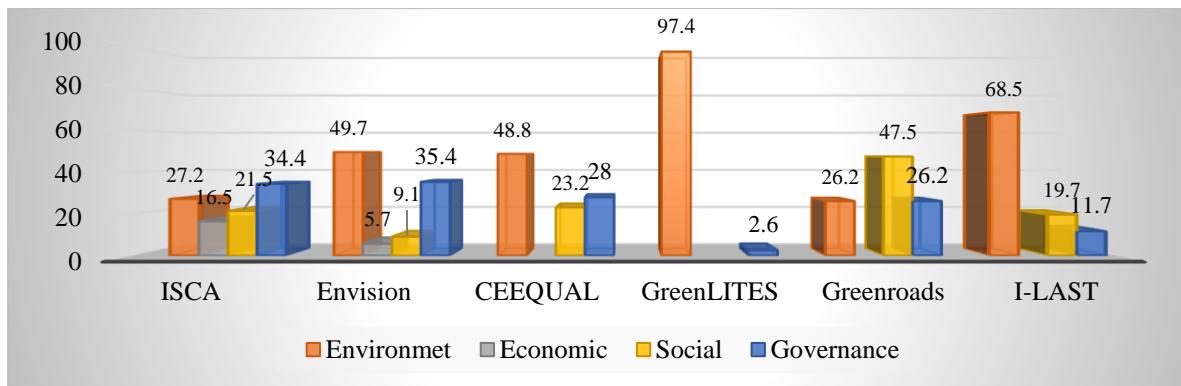


Figure 2. Percentage of Weights for each aspect under the Sustainability-rating Tools

2.2 Limitations of Rating Tools

Approaches for project evaluation other than sustainability-rating tools are available, for example, economic analysis, financial analysis, life-cycle analysis, environmental impact assessment, and social impact assessment. However, while all of these assessment methods can help to evaluate the performance of infrastructure projects in multiple dimensions, including social, economic, and environmental, these approaches are often used individually or separately [12]. The separate evaluations do not balance, and trade-offs between different aspects of evaluation lead to the risk of overlap, omission, and inconsistency in evaluating the sustainable performance of a project [13]. A lower level of consideration of the dynamic relationships and cohesion between different sustainability criteria also makes it difficult for different project stakeholders to act in cohesion to improve a project's sustainability performance [14].

2.3 Dynamic Approach in Sustainability Assessment

Zietsman and Rilett have proposed two basic principles of sustainability-related to transportation infrastructure, stating that these principles must also be mimicked by the assessment tools [15]. The two principles are multidimensionality (interrelationships between the sustainability aspects of a project) and dynamics (necessity to adapt to the changing needs of society and future generations over time) [14]. However, these rating tools are unable to address and express the complex relationships among the various sustainability criteria, and each criterion must be assessed in isolation irrespective of the fact that all criteria are interrelated and must be dynamic [14]. Therefore, a conceptual framework proposed in this paper applies a dynamic approach using System Dynamics (SD) modelling approach that can not only consider interrelationships of the variables collectively but also take into account the impact of dynamic variables.

2.3.1 Examination of dynamic interactions between sustainability criteria

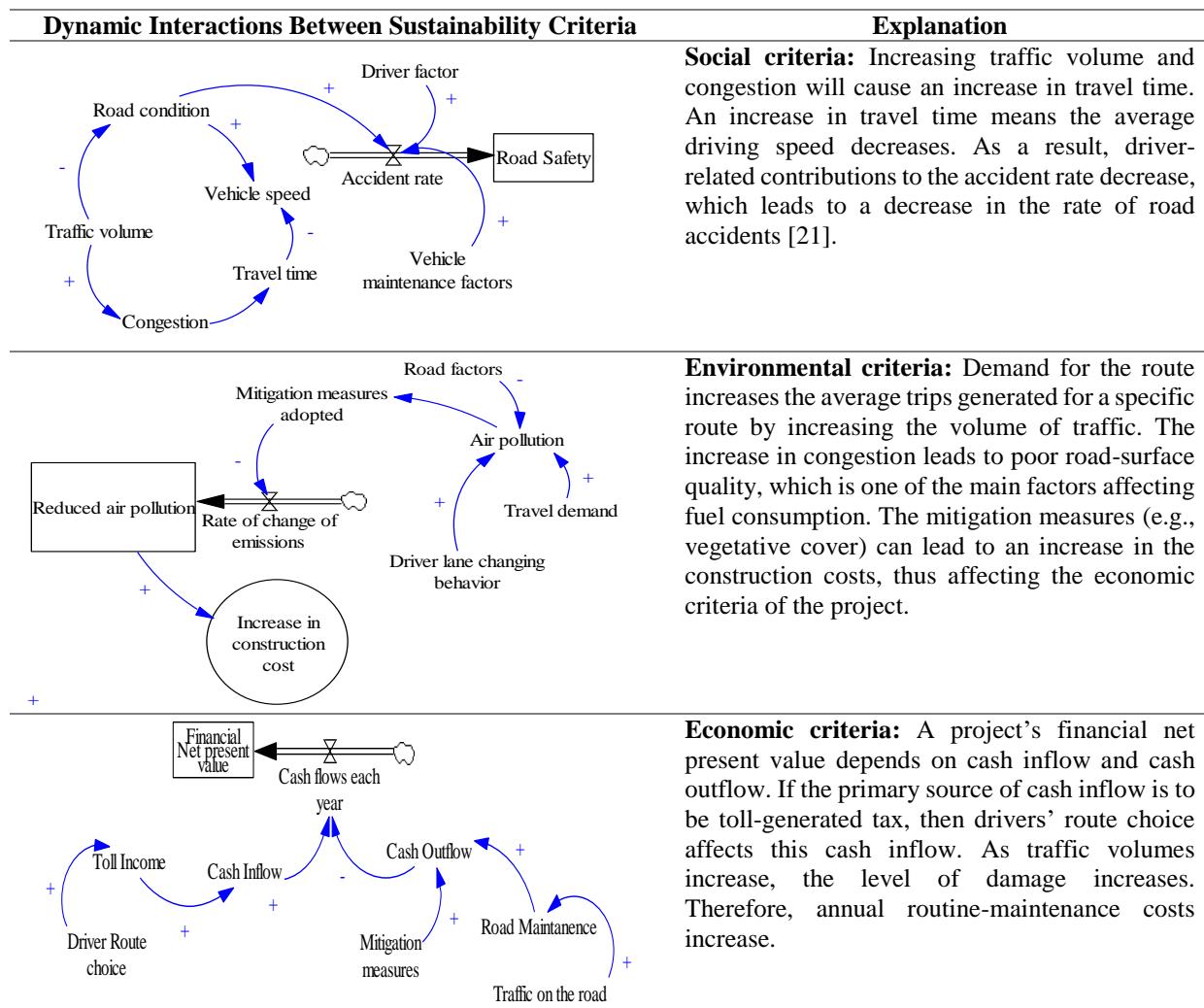
The growth of the dynamic aspects of any public-investment project can be explained on two levels: the dynamics at the macro-level (system level) and the dynamics at the micro-level (individual level) [16]. In the context of road-infrastructure projects, the dynamics at the micro-level arise from the road users who utilise the investment project during the operational phase. The road user has a substantial effect on the project because they create a demand that significantly affects the performance of the project [16]. Further, road users while utilising the road during travelling interact with one another following their individual decisions and the imposed rules that change over time. These micro-level dynamics that the road user creates influence the macro-level system dynamics of the project. Thus, it is difficult to predict the performance of a project concerning its macro and micro-dynamics through a traditional cost-benefit analysis and the available sustainability-assessment tools, which are usually static [17]. However, this paper only focuses on macro-level dynamic variables of sustainability as data

needed for micro-level (road user behaviour) dynamics is much complicated and requires additional modelling methods along with system dynamics.

The macro-level dynamics are explained by considering one criterion from each of the sustainability aspects explained in Table 4. For example, the noise emissions from the environmental aspect can be affected by the traffic volume generated, and the pricing strategy from the economic aspect can be affected the route choice behaviour of road users [18]. Similarly, when a noise-mitigation measure is adopted, the cash outflow of the infrastructure project increases [18]—a graphical representation of these dynamic interactions among the criteria are presented in Table 4. The causal-loop diagram has been utilised to describe these interrelationships in the system-dynamics domain. In system dynamics, relationships among the criteria is a closed-loop system to prevent any obstacles in information flow [19]. The feedback effect of closed-loop system can be positive or negative. A positive effect is when an increase or decrease in any criteria results in an increase or decrease, respectively, in related areas [19].

In contrast, with a negative effect, an increase or decrease in any variable will result in a decrease or increase, respectively, in related areas. Positive (+) signs on the arrows in the causal loop diagram indicate a reinforcing (increasing) effect of one parameter on another parameter, whereas negative (-) signs indicate a balancing (decreasing) effect of one parameter on another parameter [20]. Some of the significant feedback loops of the different aspects of sustainability are described in Table 4.

Table 4. Dynamic Interactions between Sustainability Criteria [21]



2.4 Conceptual Framework for Dynamic Sustainability Assessment Analysis

Research efforts have been carried over the last few decades towards studying the modelling process in adopting the system dynamics methodology [18] [19]. Figure 3 presents the various steps required for executing an SD model that can be utilized for dynamic sustainability assessment of road projects. The first step requires an understanding of the system and its components. This is necessary to identify the major cause and effects and derive feedback and causal loops of different variables. Later, the system model is constructed, logical and mathematical formulations among different components are drawn. While road infrastructure sustainability assessment using such modelling process can be a complete quantitative approach. However, in the case of a new system, it is very hard to decide which components are important in developing the SD model and relations that exist among them [20]. Under such circumstances or when the system has a high degree of complexity, it is better to have a clear purpose of modelling and focus on the problem, its causes, and subsequent effects [20]. Finally, the model should be run for simulating different scenarios, estimating the impact of alternative policies, and summarizing policy recommendations.

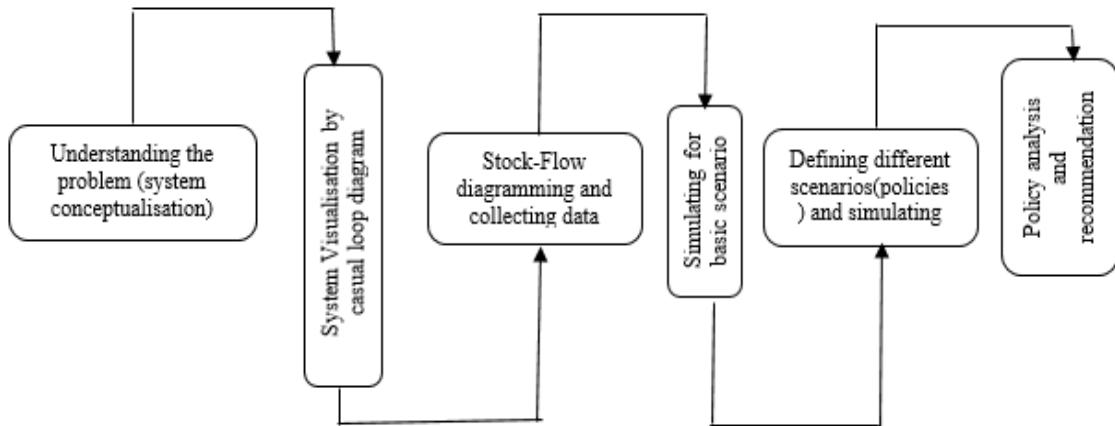


Figure 3. The modelling process in applying System Dynamics approach

The proposed modelling approach shown in Figure 3 allows the modeller to quantitatively estimate and evaluate road system performance, and analyze the behaviour in response to external changes, for example, regulatory policies like trip sharing, car ownership, etc.

3. CONCLUSION

The currently available approaches to dynamic sustainability assessment are minimal and limited. In particular, the attempt to consider the micro-level and macro-level analysis of the dynamic evaluation of sustainability performance is rarely found in road infrastructure projects. The behaviour of road users is the essential element to be considered by project organisers because it significantly affects the overall sustainability performance of the project. Given that the road-user behaviour emerges from diverse aspects, and is therefore difficult to predict and require additional simulation techniques utilised by traffic engineers. Thus, this paper provides a valuable approach for analysing macro-level system dynamics to deliver sustainable road networks by proposing a conceptual framework that helps policymakers to simulate a series of experiments. The great advantage of the proposed framework is that it allows evaluation through consideration of dynamic environments such as changes in population growth and needs, political agendas, and regional climate change.

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XXI. BIG DATA AND AI LEARNING III (G3)

Real-time Knowledge Structure Mapping from Twitter for Damage Information Retrieval during a Disaster

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Abstract: Twitter is a useful medium to grasp various damage situations that have occurred in society. However, it is a laborious task to spot damage-related topics according to time in the environment where information is constantly produced. This paper proposes a methodology of constructing a knowledge structure by combining the BERT-based classifier and the community detection techniques to discover the topics underlain in the damage information. The methodology consists of two steps. In the first step, the tweets are classified into the classes that are related to human damage, infrastructure damage, and industrial activity damage by a BERT-based transfer learning approach. In the second step, networks of the words that appear in the damage-related tweets are constructed based on the co-occurrence matrix. The derived networks are partitioned by maximizing the modularity to reveal the hidden topics. Five keywords with high values of degree centrality are selected to interpret the topics. The proposed methodology is validated with the Hurricane Harvey test data.

Key words: Damage information retrieval, Deep learning, Disaster management, Knowledge structure, Twitter

1. INTRODUCTION

Disaster has caused severe impact on human society including damage to property, business interruption, and casualties [1]. These damages can lead to huge economic losses as well as restrictions on social activities. As the frequency and intensity of disasters increase due to climate change, the scale of social and economic damage caused by disasters is increasing [2]. It is required for an effective disaster management system to alleviate the enormous social and economic damage originated from disasters. Establishing a response plan is a particular step of disaster management that refers to a process of suppressing the spread of damage during a disaster. Since the spread of the damage are directly correlated to the volume of the social and economic losses, an adequate response plan should be established in a timely manner. When it comes to organizing a timely response plan, the critical factor is to promptly obtain high-quality situational information. Thus there is a need for a channel where it constantly provides high-quality situational information

Twitter is one of the suitable channels to obtain abundant information persistently as it is characterized by the active sharing of situational information among users who are scattered across large areas in disaster situations. Although a large amount of information is underlain on Twitter, the

information includes both relevant and irrelevant information to understand the damage situation. The process of classifying relevant information should be carried out to completely utilize Twitter as medium to recognize damage in the society. The relevant information classified by time contains several types of damage. It is crucial to detect the types of damage as they give a clue for which damage type should be focused on priority when establishing a response plan. Attempts have been made to detect topics shared on Twitter [3]. However, there were few studies that focused on the topic change in damage-related information despite this information is the basis for establishing a response plan according to time.

Knowledge structure mapping refers to the process of defining the interrelationships of concepts that make up a single knowledge. This concept has been widely used to discover research trend in various domains such as library and information science, medical education [5, 6]. As well, this concept can be utilized to identify topics by keywords from a large amount of data produced on Twitter. Therefore, this paper proposes the knowledge structure mapping methodology that effectively identifies the topic change in damage-related information. Firstly, the damage-related information is classified by the state-of-the-art deep learning model, Bidirectional Encoder Representations from Transformer (BERT) [7]. Then the topics for damage-related information are identified with the keywords based on the network theory. The proposed methodology is validated through the Hurricane Harvey test data.

2. METHODOLOGY

2.1. Damage-related tweets classification through a BERT-based approach

In the early days when deep learning was applied for natural language tasks, models such as SVMs, Naïve Bayes, and CNN were dominant. However, these models had limitations that they could not reflect word order information well. If the order information of words is not reflected, it is impossible to grasp the entire context. In other words, those models could not capture the different usage of the same words in different sentences. Recurrent neural networks (RNNs) and long short-term memory networks (LSTMs) have been proposed to reflect word order information. These models are recurrent models, using the previous hidden state to compute the current output. However, they have a disadvantage in terms of forgetting prior information when the text is long. Transformer, unlike the existing RNNs or LSTMs, learns the dependency of input and output using attention mechanism instead of recurrence. This compensated for the loss of information when the preceding and subsequent words were far apart.

In this study, the initialized pre-trained parameters of BERT were fine-tuned to reflect the semantic representation of damage-related tweets via transfer learning. The BERT-Base model was employed to achieve the given task. The specific task was to classify a tweet into one of the four classes that are related to human damage, infrastructure damage, and industrial activity damage: “Dead, Injured people,” “Found people, Evacuation, Rescued,” “Infra, Industrial activity related,” and “Missing, Displaced, Trapped people”. The data downloaded from CrisisNLP [8] and CrisisLex [9] were used for the model fine tuning. The number of labeled tweets for each class is summarized in Table 1. In order to determine the optimal hyperparameters, the data was split into train and validation data by an 80:20 ratio. The optimal hyper parameters were determined when the loss of the validation dataset was minimized. The damage-related tweets in the Hurricane Harvey (August 25, 2017, 14:44~15:13) were downloaded from creative commons (open source data with no copyright) for the test data to evaluate the performance of the BERT model.

Table 1. Data description for model training and test.

Class	Training data	Test data
Dead, Injured people	338	6
Found people, Evacuation, Rescued	291	93
Infrastructure, Industrial activity related	274	181
Missing, Displaced, Trapped people	162	4

2.2. Knowledge structure mapping

The knowledge structure mapping refers to the process of discovering topics that are discussed in “Dead, Injured people,” “Found people, Evacuation, Rescued,” “Infra, Industrial activity related,” and “Missing, Displaced, Trapped people” by keywords with the passage of time. The relationship between words is represented with nodes and edges based on the co-occurrence matrix. The node stands for a word and the edge stands for the number of the co-occurrence between words. The length of the edge indicates how strongly the nodes are related. The smaller the edge length, the stronger the node is connected. In other words, the edge length is small when the number of the co-occurrence is large. Community detection is a way of partitioning the network on the basis of modularity, the criterion to measure the quality of the partition. This paper performed the community detection based on the algorithm suggested by Blondel et al. [10].

3. RESULT AND DISCUSSION

The values of optimal hyperparameters were as follows: 128 for sequence length, 30 for batch size, 7 for epochs, and 1e-4 for learning rate. Using the BERT model fine-tuned with the given data, the Hurricane Harvey test data was categorized into the 4 classes. Accuracy, precision, recall, and F1-score values were obtained for each class. The results are summarized in Table 2. The macro average of the F1 scores is 85% and the weighted average (considering the number of data in each class as weight) of F1 score is 96%.

The network was visualized with the open software Gephi [11], as shown in Figure 1. The size of the node is proportional to the frequency of nodes and the thickness of the edge reflects the closeness between words. The nodes that are clustered into the same community are expressed in the same color. The set of the words with high centrality values are the keywords that stand for the clustered community. In this study, the top five keywords with high centrality values were selected to interpret the topic of the community. The keywords that made up the communities in “Infrastructure, Transportation damage” are summarized in Table 3. The topics for the six communities were interpreted as follows: “Gas price rise” for community 1, “Airport damage due to storm” for community 2, “road and pump damage” for community 3, “The open of border patrol checkpoint” for community 4, “Interruption of communication” for community 5, “postponement of sporting Kansas City (KC) match” for community 6, and “nuclear power in damage” for community 7.

Table 2. Precision, recall, and F1 score for four classes.

Class	Precision	Recall	F1 score
Dead, Injured people	0.80	0.67	0.73
Found people, Evacuation, Rescued	0.99	0.95	0.97
Infrastructure, Industrial activity related	0.96	0.99	0.98
Missing, Displaced, Trapped people	0.75	0.75	0.75
Macro average	0.88	0.84	0.85
Weighted average	0.96	0.96	0.96

Table 3. The keywords for the communities in “Infrastructure, Industrial activity related”.

Community	Keywords
1	gas, prices, texas, us, rise
2	storm, surge, airport, superstorm, expect
3	water, approaches, capacity, pumps, road
4	Open, patrol, border, checkpoints, stay
5	Stop, working, cell, phones, daysweek

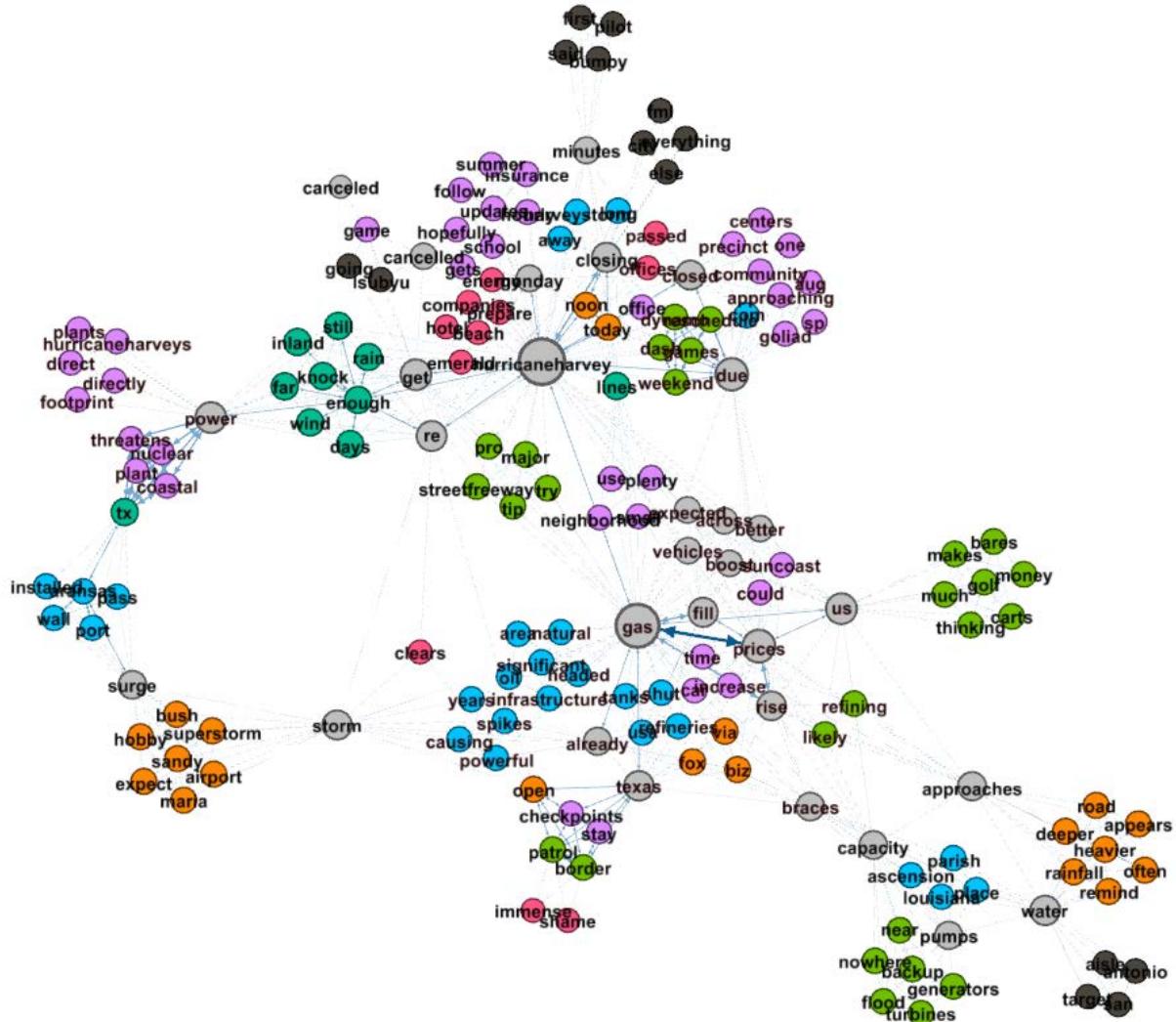


Figure 1. Knowledge structure for “Infrastructure, Industrial activity related”.

4. CONCLUSION

The damage information shared on Twitter can be used for establishing a response plan in a timely manner. However, it is a challenging task to identify the damage-related topics in the stream of large data. To address this problem, this paper proposes an effective methodology to identify the damage-related topics in real-time by constructing a knowledge structure with the combination of the BERT-based classifier and the community detection techniques. A case study of Hurricane Harvey validated the applicability of the proposed methodology. The proposed model can be improved by collecting supplementary tweets to reflect the diverse expressions used in the damage-related tweets. The geospatial information could be used with the derived knowledge structure to specify the area where the specific damage happened. With the improvement, the knowledge structure obtained from the study is expected to be used as a basis for preparing an efficient countermeasure to disasters.

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The Architecture of an Intelligent Digital Twin for a Cyber-Physical Route-Finding System in Smart Cities

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Abstract: Within an intelligent automated cyber-physical system, the realization of the autonomous mechanism for data collection, data integration, and data analysis plays a critical role in the design, development, operation, and maintenance of such a system. This construct is particularly vital for fault-tolerant route-finding systems that rely on the imprecise GPS location of the vehicles to properly operate, timely plan, and continuously produce informative feedback to the user. More essentially, the integration of digital twins with cyber-physical route-finding systems has been overlooked in intelligent transportation services with the capacity to construct the network routes solely from the locations of the operating vehicles. To address this limitation, the present study proposes a conceptual architecture that employs digital twin to autonomously maintain, update, and manage intelligent transportation systems. This virtual management simulation can improve the accuracy of time-of-arrival prediction based on auto-generated routes on which the vehicle's real-time location is mapped. To that end, first, an intelligent transportation system was developed based on two primary mechanisms: 1) an automated route finding process in which predictive data-driven models (i.e., regularized least-squares regression) can elicit the geometry and direction of the routes of the transportation network from the cloud of geotagged data points of the operating vehicles and 2) an intelligent mapping process capable of accurately locating the vehicles on the map whereby their arrival times to any point on the route can be estimated. Afterward, the digital representations of the physical entities (i.e., vehicles and routes) were simulated based on the auto-generated routes and the vehicles' locations in near-real-time. Finally, the feasibility and usability of the presented conceptual framework were evaluated through the comparison between the primary characteristics of the physical entities with their digital representations. The proposed architecture can be used by the vehicle-tracking applications dependent on geotagged data for digital mapping and location tracking of vehicles under a systematic comparison and simulation cyber-physical system.

Keywords: Autonomous Route Finding, Digital Twin, Smart Cities, Intelligent Cyber-Physical Systems, Regularized Least-Squares Regression

1. INTRODUCTION

The infrastructure of a smart city is founded upon a network of sensors and actuators embedded across the urban area, interacting with a multitude of wireless mobile devices (e.g., smartphones) under a responsive cloud-based network architecture [1]. Such a system requires an integrated cyber-physical

infrastructure with various software platforms for securely processing massive amounts of information. Major physical infrastructures in cities, such as transportation systems, are part of a spatial-temporal, large-scale connected system that bridges humans and technology through numerous sensors [2]. Yet conventional transportation systems have not achieved full coordination and optimization due to a lack of widespread interconnection, intercommunication, and interoperability [2]. In this regard, recent advancements in information technologies, such as the Internet of Things (IoT), cloud computing, and Cyber-Physical Systems (CPS), have provided the opportunity to address emerging challenges that arise in urban traffic systems. Accordingly, various monitoring devices and sensors can be installed on roads and vehicles to largely collect and timely process traffic information so as to provide real-time status models of vehicles [3]. Particularly, cyber-physical systems with their integrated computational and physical components can be leveraged to collect such big data, elucidate latent patterns from the data, and generate information-rich feedbacks to the users, effectively and efficiently. In the context of CPS, a digital twin of the system can address the challenges pertaining to poor data management and low prediction accuracy of the system. In this regard, a digital twin is distinguished from other simulation approaches in that it can synchronize digital constructs based on real assets, actively record data from the real environment, and sufficiently simulate real-world mechanisms and operations [4]. Given these qualities, integrating the intelligent digital twin with cyber-physical route-finding systems can provide the means for better system management and lead to a robust realization of autonomous mechanisms within transportation systems.

Most of the transportation systems, particularly in the United States, benefit from easy and free accessibility to real-time Global Positioning System (GPS) data of public vehicles [5]. The embedded GPS devices in these “physical systems” send the location of the vehicles to a cloud server, which later can be publicly accessed through simple text-based queries, such as JSON. The retrieved data can be analyzed quickly using ubiquitous smartphones equipped with high-computing power and miniaturized high-density sensors [5]. Considering these capabilities, GPS data is widely utilized to estimate the arrival time of public vehicles, especially public buses [6–8]. However, these GPS-based systems are prone to several errors, such as location update delay or non-accurate location data. Notably, it would be challenging to estimate bus arrival time accurately due to traffic, dwell time at the bus stations and intersections, and unpredictable events, such as accidents or roadwork. On the other hand, not all the route information retrieved from public servers is accurate and up to date. In other words, although the server can provide various bus routes to the user, in most cases, the polygons representing these routes do not reflect their latest changes nor their correct directions. The accessibility to the precise geometries and directions of these routes is of utmost importance as most of the bus-arrival algorithms depend on the correct location and sequence of the constructing points [9].

As a response to this challenge, this study attempts to develop a digital twin of a transportation system by proposing an intelligent cyber-physical route-finding conceptual framework capable of automatically construct and evaluate routes with accurate direction and geometry and continuously estimate the arrival time of the buses on those routes. The cyber-physical part of this framework is built upon two chief constructs, an automated route-finding process by which the polygon representing the route can be accurately inferred and a bus-arrival time estimation system that can intelligently monitor all the operating vehicles on a specific route and provide the user with a relatively accurate arrival time of the next closest vehicle on that route. Such a system obtains real-time GPS data from an online server and stores them on a workstation. Once a sufficient number of points are collected for each route, the system uses a least-square regression algorithm [10,11] to approximate the polygon representing the route. Afterward, it leverages the Google Map matching Application Programming Interface (API), in real-time, to correct and verify the resultant route. This procedure ensures that the bus follows the logical path and has not left the route for a certain reason (e.g., gas filling). Finally, the retrieved route is discretized to small pieces upon which the location of the vehicle can be mapped, and the bus-arrival algorithm can be built. These automated route-construction and vehicle-mapping procedures will then be used to simulate and manage the physical entities of the systems. By implementing the proposed approach on an Android smartphone, a workstation, and a cloud server, the digital twins of the vehicles and the buses were constructed. Specific characteristics of these digital representations were compared with those obtained from their real-world entities to evaluate the performance of the cyber-physical system. The findings of this study can pave the way to establish a more efficient transportation system to improve the daily experience of city dwellers. The remainder of this paper is organized as follows. Section 2 introduces the background and motivation of this study. Section 3 outlines the overall

architecture of the proposed approach. Section 4 elaborates on the results of the framework implementation. Finally, Section 5 presents the discussion and conclusion.

2. RESEARCH BACKGROUND

There is a great potential for CPS to address one of the main challenges of the people living in big cities, robust, reliable, and convenient transportation. The integration of big data analytics and high-density sensed data enables policy-makers to accurately elicit beneficial information from the urban environments, various entities, and citizens. Cyber-physical systems are a synthesis of digital content and cyber methods with physical processes in which embedded computers control the physical processes using feedback loops, and physical processes affect computations [12]. One application of CPS in the transportation area is to transmit the information of physical transportation objects to the cyber system to achieve information communication, system coordination, and optimal decision-making control of the transportation system through the interaction and feedback between the physical and cyber systems [2]. In this regard, the digital twin of a system can be regarded as a virtual representation of a physical asset in a CPS, capable of reflecting its static and dynamic characteristics [4]. Essentially, a digital twin of an asset must inherit all the functionalities that the asset is able to perform in the real world. An intelligent digital twin, therefore, can potentially implement different machine learning algorithms on available models and data to optimize a variety of operations in a transportation system.

The integration of GPS traces and smartphone applications for transit tracking systems has been among the new emerging real-time tracking technologies in the past few years [13–15]. The extensive research in the transit tracking systems and supporting applications is due to the availability of the all-embracing, ubiquitous smartphones, affordable and accurate GPS, fast internet speeds, and optimized smartphones' operating systems, such as the latest versions of Android and IOS. Interestingly, not only smartphones provide the users with adequate computational power for running these types of tracking-based applications, but the availability of powerful and well-known APIs such as Google map API enhances the accuracy and usability of such systems as well. Generally, the architects of such systems rely on three key components, namely Automatic Vehicle Locator (AVL), online server, and smartphone devices [13]. Although the exhibition of real-time vehicle's positions on digital maps, based on their AVL GPS data, is exceptionally informative to the users and works well with the current technologies, the accurate estimation of the vehicle's arrival time would be hard to accomplish. The main obstacles to correctly estimating bus arrival time are the fluctuation of delay times at intersections, dwell time at stops, and travel speed of the operating vehicles. To overcome these barriers, numerous studies started to implement various efficient techniques such as deep learning and neural network into the AVL transit systems [16–20].

Following the trend towards new arrival time predicting approaches, parallel to the manifestation of new transit tracking systems exploiting smartphones, researchers started to present innovative vehicle arrival time algorithms mostly concentrated on bus tracking applications [13,18,19]. In 2010, Thiagarajan et al. presented a cooperative transit tracking system that significantly lowers the commuter wait time. With the help of power-efficient and resourceful algorithms pertaining to activity classification, route matching, and underground vehicle tracking, they were able to reduce the wait time by more than 2 minutes, with only 5 percent of the riders using such a system [19]. Biagioni et al. presented smartphones as cheap AVLs, alternative to more costly GPS devices, that resulted in a cost-efficient arrival estimating application [13]. Besides, as mentioned above, with the rise of new machine learning techniques, some of these prediction algorithms have been accustomed to the machine learning models trained by collecting data from the vehicles operating on the known routes. For example, by collecting data from the bus transit system in Sao Paulo, Brazil, and subsequently utilizing machine learning techniques, Nissimoff was able to predict the bus arrival time with acceptable accuracy [18]. Similar research presented Support Vector Machines (SVM) as a feasible and applicable technique to predict bus arrival time in China. However, Bin et al. stated that the SVM approach for predicting bus arrival time works more accurately if the real-time data from traffic surveillance systems are available [16].

By considering the aforementioned techniques in predicting the bus arrival time, a significant number of studies utilized the routes of the network as a known unchanged polygon by which the location of the vehicle could be mapped correctly on the digital map [21–25]. However, in many cases, the availability of the updated route geometry information is costly and time-consuming, even though the operating vehicles' locations can be retrieved seamlessly and with short interval time. Bearing in mind these

crucial caveats in designing AVL tracking-based applications, one might think of an approach that would exploit real-time GPS data of the operating vehicles on a specific route and indirectly draw the corresponding route. If drawn correctly, the information about the geometry of the route, and perhaps the direction of the path, would always be updated with minimum maintenance cost. This is a fundamental pre-processing step for these types of transit tracking systems and many other tracking-based ones. To that end, numerous studies offered map-matching algorithms that would use GPS data of the operating vehicle as input and present the geometry data of the route as an output [26–28]. In terms of accuracy, by introducing innovative approaches, some of these map-matching techniques vastly surpass others [29,30]. Lou et al. proposed a map-matching algorithm, “ST-Matching,” for low-sampling-rate GPS data that outperforms other famous techniques such as Average-Frechet-Distance (AFD) [31] and incremental algorithms [27]. In their ST-Matching algorithm, the candidate points are selected based on the spatial analysis of geometric and topological information of the road network, which later will be used to “logically” match the selected points on the digital map [30]. Another critical factor in the cost-effective tracking-based applications is the information about the precise geometry and direction of the roads on which the operating vehicles are being tracked. Fortunately, there are many services that provide such a service to the users; however, they are not free for more than a specific number of quarries per day. For instance, Google presents a robust and accurate map-matching API, free of charge for a certain number of quarries per day [32]. Therefore, designing a tracking algorithm to use a smaller number of quarries would be a wise approach to achieving cost and time-effective route-updating and map-matching algorithms. To that end, the first step is the preparation of the raw cloud of data for exportation to the server. Using famous regression algorithms, it is possible to reduce the number of nominated points for exportation and, consequently, the number of quarries from the online server. By implementing map-matching techniques into a transit tracking system, the current study endeavors to (1) provide accurate routes’ geometry and direction to the users’ tracking applications, and (2) use a new simple arrival time algorithm that optimizes the time and data consumption for monitoring and subsequently predicting the arrival times of the buses.

3. METHODOLOGY

3.1. Cyber-physical transportation system

The first step towards generating the automated cyber-physical transportation system is to extract the route information from raw GPS data. In order to do that, a computer needs to retrieve the GPS locations of the desired vehicles (i.e., public buses) operating in a specific area from an online server. Upon successful server responses, useful information, such as vehicles’ latitude and longitude, speed, angle, identification number, and representing color, can be acquired and used for data analysis. For data analysis, the proposed algorithm must be able to perform the following tasks:

1. Create vehicle objects based on the number of active vehicles operating on the route exploits the server’s JSON response.
2. Logically update the location of the vehicle objects from the server based on their distance to the target destination on the route.
3. Detect the operating hours by storing the time of the first and last vehicles operating in a day.

Once the cloud of GPS locations for each route is obtained, an appropriate analytical method must be selected to provide an approximate polygon representation of the route. To that end, the regularized least-square (with norm-2 penalty) regression algorithm is employed to determine the geometry of the route. It is worth mentioning that this step is essential in removing the GPS data collected while the bus was leaving the route (e.g., gas filling or end of operating hours). Subsequently, the filtered data points, which are passed from the regression (points within the penalty range) algorithm, would be uploaded to the Google server using Google’s map matching API. The response from the Google server should contain the accurate location points with which the precise polygon representation of the route can be constructed. Notably, the proposed technique requires the least number of queries from Google’s map matching API because only the “approved” location points would be sent for the map matching process.

The next step is to identify the direction of the route based on the time tags of the data points retrieved earlier from the vehicles. As each GPS data point has a time tag from the retrieval time of the vehicle location, the sequences of the “approved” points for route construction can be identified. In this vein, the final points of a specific route in the system have time tags that determine that route’s direction. The last step towards an intelligent cyber-physical transportation system is to map the location of the

operating vehicles on their corresponding maps by which the arrival time of the vehicle can be estimated. This mapping procedure can be accomplished by finding the points on the route within the proximity of the near-real-time location of the vehicle and selecting the closest point that complies with the direction of the vehicle. Such compliance can be examined by considering the previous locations of the vehicle that can delineate the direction of the vehicle. Figure 1 provides the overall procedures of the proposed cyber-physical system for automated bus-arrival estimation.

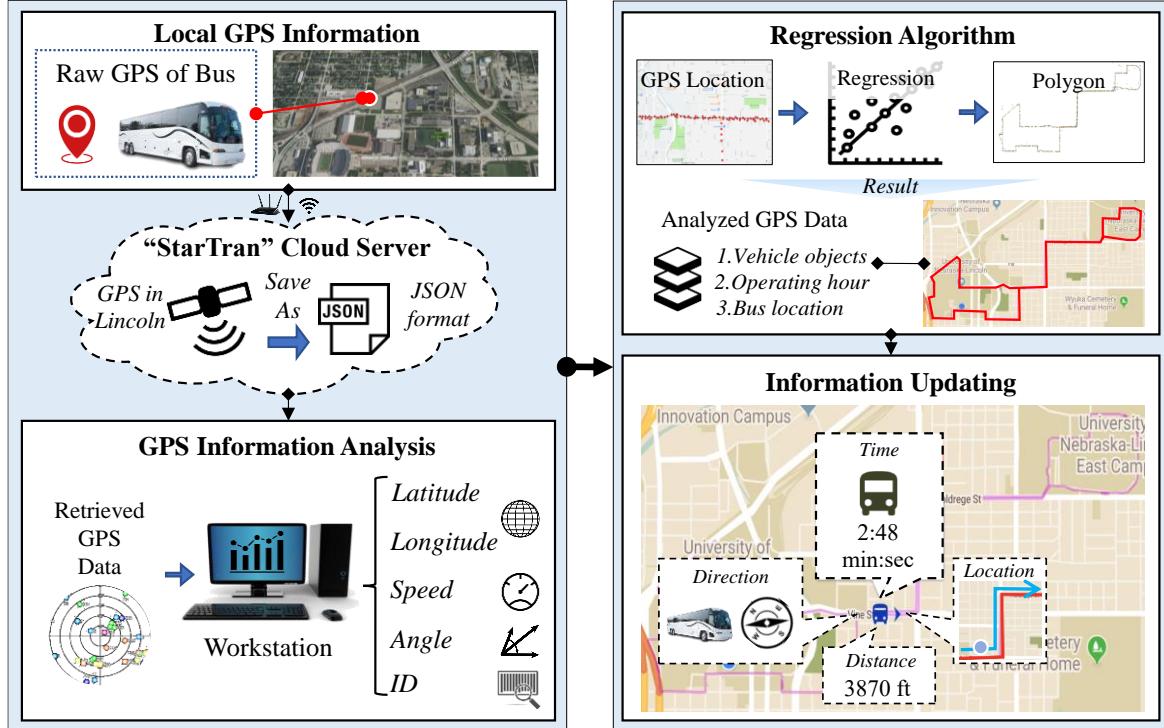


Figure 1. The overall procedure of the proposed cyber-physical route-finding system

3.2. Case Study

To evaluate the feasibility and efficiency of the proposed approach, a case study was designed based on Lincoln's public transportation system. To construct the cloud of geotagged data points, the real-time locations of the vehicles operating on route #24 of the Lincoln transit network, StarTran, have been used. The StarTran server [33] is a public server on which the near-real-time locations of the operating vehicles are available. This server is used for the presented case study. The GPS information of the buses operating in Lincoln is available through JSON queries. Accordingly, thirty-six loops of these operating vehicles have been retrieved from the server to construct a specific route. Afterward, by considering the “average” feature for these points, the “outliers” have been identified and removed from the data set. In this case, more data collection from the operating vehicles would result in more accurate route construction and outlier detection. In the next step, all the points have been connected to form a polygon that represents the route. Finally, by following the real-time mapped location of an operating vehicle on route #24, the direction of the route has been determined. The following steps specify the procedures necessary to construct a directed route from a cloud of geotagged time series data:

1. Create a polygon from the filtered points by using the least square regression algorithm.
2. Establish an accurate polygon by using the Google map matching API on the current polygon.
3. Equally, divide the accurate polygon into small lines to construct new polygon representation points.
4. Set time T to zero. Then, at each Δt_i , find the closest point p to the real-time location of the operating vehicle and add the pair $(p_i, \Delta t_i * i)$ to the polygon array list P_n in which n represents the route number.

The resultant P_n represents the route with the correct direction. After constructing the directed route, the estimation of the arrival time of the operating vehicles on route #24 would be possible. To that end, the location of the buses should be correctly mapped on the route. In this case, the direction of the route plays an essential role in choosing the final mapped location. The reason lies behind the fact that the precision of the GPS devices mounted on the operating vehicles is not accurate enough to distinguish

between real locations of the buses on closed lines of the polygon representing the route. To overcome this barrier, the direction of the vehicle should be accounted for the correct mapping process (Figure 2). Accordingly, the necessary steps to correctly map the bus location on the route are as follows:

1. Find the five closest points on the route to the vehicle location, sorting them based on their distance, and finally storing them in the *old_closest* array
2. Wait for the new location of the vehicle from the server. Once retrieved, proceeding similar to step one but storing the points in the *new_closest* array instead
3. For each of the points *old_closest*[*i*] in the *old_closest* array, loop over the point *new_closest*[*j*] in the *new_closest* array.
4. If the time label of the point from the old array is less than the one in the new array, and the difference between the indices of points of the route is less than a threshold, accept the current point as the mapped point and break from the for loops.

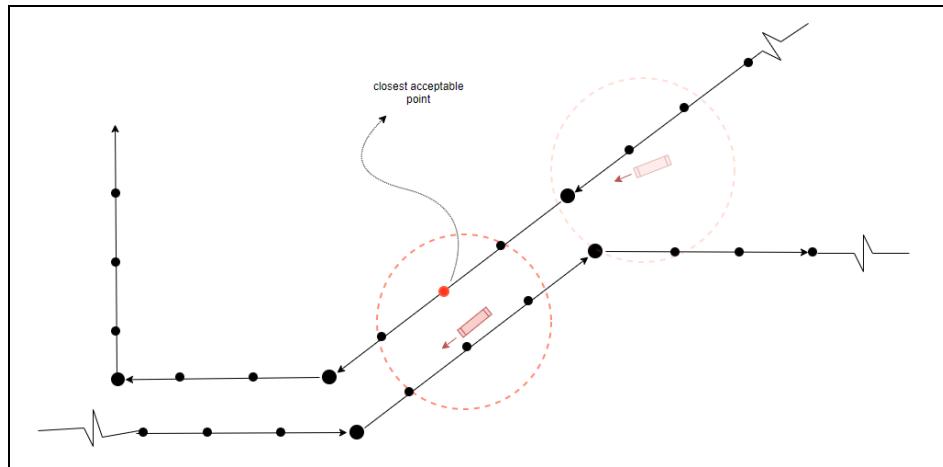


Figure 2. Schematic representation of the general idea to map the location of the bus on the constructed route

The resultant route-finding and location-mapping algorithms serve as the backbone of the automated cloud-based transportation system. This system can then be visualized, managed, and evaluated through a constant comparison between the real-world buses and routes and their digital replica. Figure 3 demonstrates the overall digital twin functionality of the proposed cyber-physical transportation system that suggests the feasibility of using such an approach to compare the results of the simulations in an attempt to manage and improve the system.

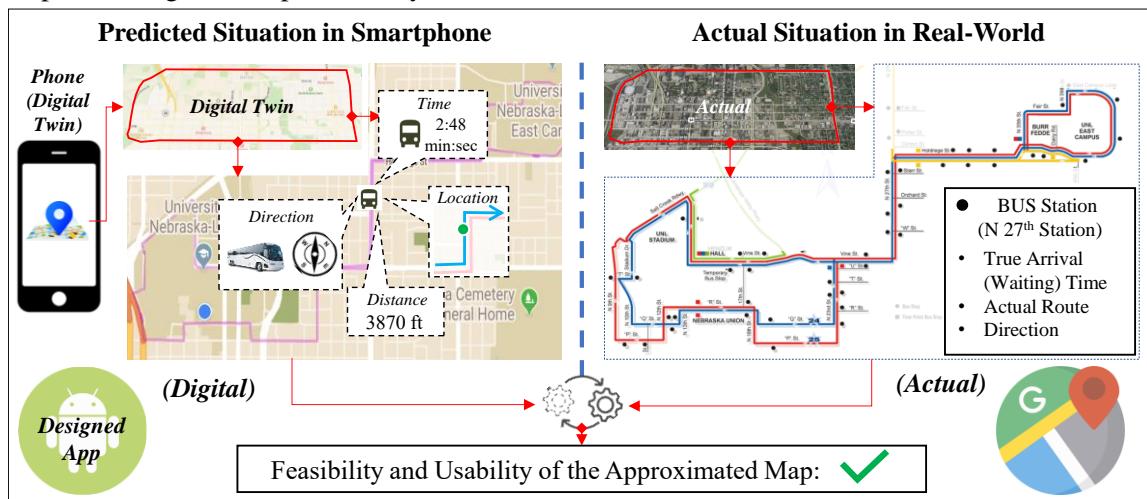


Figure 3. The comparison between the proposed cyber-physical system and the actual situation by using the digital twin concept

4. RESULTS

Figure 4 shows the approximate route constructed by using the cloud of data. The data points visualized in this figure are the raw GPS data extracted from the cloud server. As can be seen, there are some outliers (red and blue points) in this figure. Figure 5 demonstrates the resultant polygon (pink line) superimposed on the 2D map. Such a shape was derived by employing the regularized least-squares regression algorithm (with norm-2 penalty). According to the settings of this algorithm, the ill-posed GPS points were rejected, and the route was constructed in an accurate shape.

Moreover, in Figure 6, the result of the proposed algorithm (section 3) has been used to find the distance of the bus to the user's pinpointed location, and consequently, estimate the arrival time by considering an average speed for urban operating buses. As can be seen, the vehicle's location on the route can be mapped on either the left to right or right to the left route; however, the above algorithm ensures that the correct location mapping is executed in this case. The estimated arrival time can then be calculated based on a predetermined average time and the calculated distance between the mapped location of the vehicle and the destination. Not only the estimation time can help the user become aware of the arrival time of the bus, but the continuous monitoring capability ensures that the bus will not path a certain point on the map. This critical point can be better contemplated if such a system is compared with the time-of-arrival estimations that rely on time tables that are static and do not account for delays along the route on which the vehicle is operating. More importantly, because the location of the vehicle is mapped on the directed route, the inquiry about the location of the vehicle will follow a distance-based rational pattern. More specifically, the GPS information of the vehicle will not be retrieved from the server with a high refresh rate if the distance of the vehicle to the target location is larger than a threshold. This intelligent refresh rate algorithm offers an efficient, adaptive time-of-arrival that can immensely save battery and processing within smartphones.

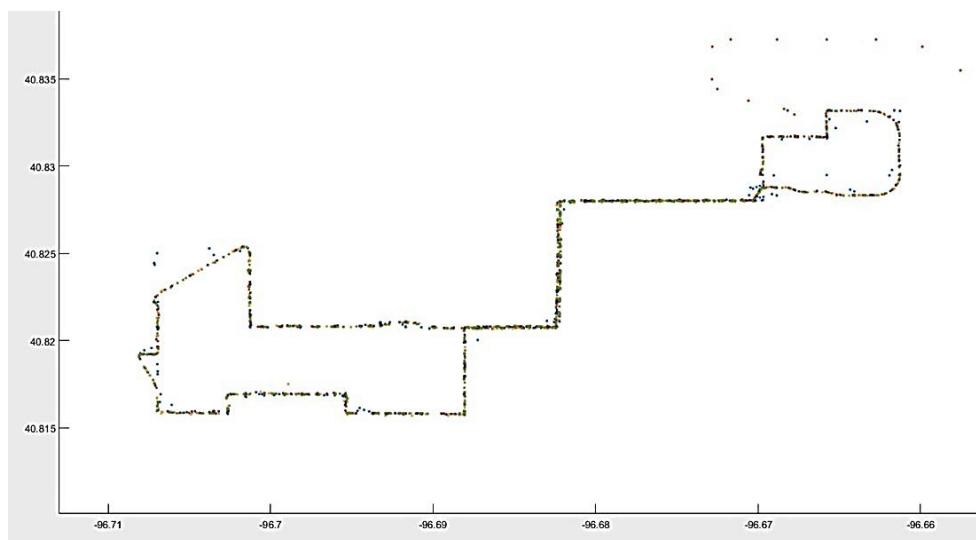


Figure 4. Results of the filtered points from the cloud of data (route #24)

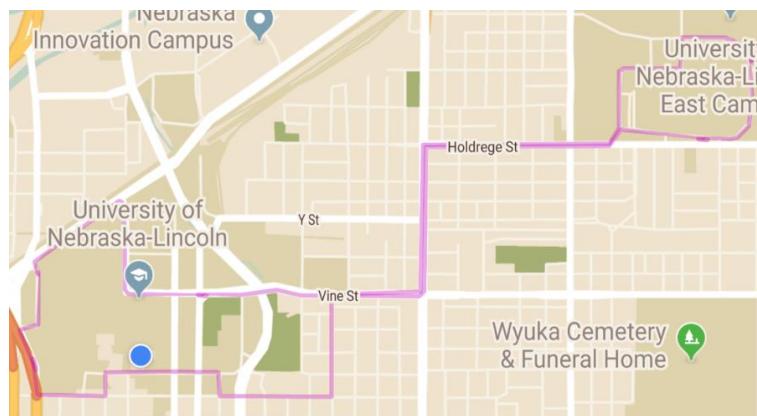


Figure 5. The final constructed directed route from the filtered cloud data.



Figure 6. Estimated arrival time based on the distance of the vehicle's mapped location on route #24

5. CONCLUSION

The incorporation of Cyber-physical Systems (CPS) in a transportation network has opened new doors in the routing and scheduling of the network. In this regard, an intelligent digital twin of the network can substantially elevate different operations across the CPS, such as data collection, data integration, and data analysis. To investigate the usability of this synthesis, this study proposes a conceptual architecture to integrate intelligent digital twin and cyber-physical route-finding system to improve the route generation and arrival time estimation of the transportation system. Using an innovative route construction methodology and algorithm, the result of this study suggests that the representation of the route geometry and direction is possible purely based on the real-time location of the operating vehicles on that route. In addition, it is indicated that the proposed bus arrival estimation algorithm can help the users to rely on the estimated time more confidently as the information will be updated regularly and intelligently. While the direction of the route is essential for the correct near-real-time location mapping of the operating vehicle, the calculated distance between the current mapped location of the bus and the user's marked location is the desired value to be found. Upon successful calculation of the latter, an informative and smart vehicle monitoring application can be developed by which the user can be continuously notified about the distance of the vehicles to his/her marked location of the corresponding route. This study demonstrated the capability of intelligent cyber-physical systems to calculate such a value by merely relying on the information retrieved from the AVLs. By using an adaptive update rate that varies based on the distance of the vehicle to the user, the present study demonstrated the suitability of the proposed cyber-physical system for smartphones as the continuous monitoring of the vehicles' locations can be computationally expensive and might consume a large amount of data. This work contributes to the existing body of knowledge by proposing an innovative framework for intelligent cyber-physical route-finding systems that can be managed, simulated, and updated under well-developed digital twins of the real-world transportation asset.

This study demonstrated the capability of the digital twin as a comparison and management tool by which the performance of cyber-physical transportation systems can be evaluated and improved. This comparison can be performed at various levels of system operation, such as the accuracy of the system feedback, the characteristics of the auto-generated routes, and the estimated arrival times. While this study proposed the idea and presented an intelligent cyber-physical system to backup that idea, the future study should exploit such potentials by more accurately simulating the physical transportation entities such as the location of the user and the travel time for each user. Also, more precise estimations of arrival time can be achieved by considering the number of turns and bus stops between the user and the vehicle's mapped location. Moreover, by utilizing the time tag for the collected data points with which the route is constructed, the program can assign different speeds to different parts of the route. This can enhance the prediction of the arrival time to a great extent. Other possible enhancements would be considering the time of day, especially the rush hours, and Google's online information of the traffic on the way.

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