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A digital construction framework integrating building information modeling and reverse engineering technologies for renovation projects

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ABSTRACT

This study proposes a digital construction framework that integrates building information modeling (BIM) and reverse engineering (RE) to improve information utilization in different phases and thus reduce mistakes and reworks in renovation projects during urban renewal. Three-dimensional (3D) laser scanning is used to enable the RE process. This framework also incorporates supporting technologies (virtual reality, 3D printing, and prefabrication) for a better understanding of design and construction as well as tools (work breakdown structure and model breakdown structure) for enhanced organization and management quality. Implementing this proposed framework in a renovated shopping center in Hainan, China optimized efficiency of the renovation process by 15%, eliminated design changes by 30% and reworks by 25%, and finally saved two months and 7.41% of cost regarding the steel structure canopy. Thus, this framework can proactively reduce occurrences of mistakes and reworks during the renovation process, greatly improving the effectiveness of urban renewal.

1. Introduction

In the fast ongoing urbanization process, the contradiction between a large population and limited land space is dramatically increasing [1]. To solve this dilemma, urban renewal has become a mainstream activity of urban development. The renewal process adjusts urban functions, reuses urban space based on actual conditions, and finally achieves transformation motivated by multiple factors (such as economy, society, and environment). Nonetheless, urban renewal mostly follows the traditional labor-intensive industry practices and tends to be slow in renovation projects [2]. Among the factors seriously affecting construction productivity in the traditional delivery, reworks are considered as non-value adding activities which consume plenty of unnecessary time, costs, manpower, and materials for correcting errors, impairing defects, implementing changes, and so on [3–6].

In urban areas most old buildings may either have lost their original design drawings or have no longer been consistent with the original drawings due to poor construction quality, construction deviation, or uninformed changes [7]. Consequently, it would take much time and money to renew projects if no original drawings are available. Even worse, if the renewal projects are guided by the inconsistent and inaccurate original design drawings, plenty of reworks may be caused.

Digital construction has emerged as one of the most useful tools to reduce reworks [8]. The current state-of-the-art approach of digital construction is to use building information modeling (BIM) and prefabricated construction (PC). According to the National Institute of Building Sciences [9], a building information model is defined as “a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition”. Thus, a project's information is integrated in a controlled virtual environment, achieving “what you see is what you get” to reduce changes and reworks. To date, BIM greatly enhances collaboration and real-time information exchange among primary project participants [10] and thus has the potential to contribute to urban renewal practices. Compared with the traditional drafting approach, BIM has many advantages, such as visualization, coordination, simulation, and optimization [11,12]. Urban renewal transforms and reconstructs old urban districts, which needs accurate information of existing buildings as a guide. Therefore, BIM implementation may contribute to enhanced quality of the entire process in renovation projects.

Previous studies have attempted to explore BIM implementation frameworks. In particular, Jung and Joo [13] proposed a comprehensive BIM framework which consisted of three dimensions (BIM technology, BIM perspective, and construction business function) and six categories to address variables for theory and implementation, but it tended to be theoretical. Singh et al. [14] developed a theoretical framework of using BIM-server as a multi-disciplinary collaboration

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platform, but mainly focused on technical requirements. Porwal and Hewage [15] proposed a BIM partnering framework which emphasized the power of engaging contractors upfront for reaping best values of BIM implementation, but focused on publicly-funded projects. However, little is known about how to implement BIM and apply these BIM-based frameworks to re-engineer the workflow and enhance the performance in renewal projects. In addition, the combination of BIM and PC needs much research in practice. It was suggested that the construction industry should learn from the manufacturing industry to drive digital planning, design, production, assembly, and management [16] to enhance information exchange and productivity of the renovation process.

This study aims to develop a conceptual framework integrating BIM and reverse engineering (RE) technologies for renovation projects. This framework involves three solutions, including: (1) combining BIM and RE to improve information utilization and exchange among major stakeholders in different phases. The emergence of RE has been well recognized during the last decade because it can facilitate secondary design in the process of renovating old buildings; (2) combining BIM and virtual reality (VR) to help the stakeholders better understand design and construction; and (3) using work breakdown structure (WBS) and model breakdown structure (MBS) to assure good organization and management quality. This study may inspire further developments to this framework and provide valuable information for both academics and practitioners in renovation projects in urban areas. The subsequent sections review BIM, RE, and supporting approaches, describe the framework's architecture, and report how this framework was applied in a renewal project in Hainan, China.

2. Issues and needs of digital construction framework in the construction industry

2.1. Reworks in renovation projects

If information is not properly exchanged and managed in procedures such as processing, transmission, acceptance, and understanding, reworks will occur. Love and Li [17] stated that reworks are unneeded efforts of redoing activities or operations that are enforced in a wrong way from the beginning. Simpeh et al. [18] found that reworks are mainly derived from uncertainties which are generated by missing, unreliable, inaccurate, or conflicting information. Thus, reworks are non-value adding and costly and often cause delays, seriously affecting the productivity and performance of construction projects. For example, Barber et al. [19] reported that reworks contributed to cost overrun (approximately 23%) of the contract value in multi-million pound major road schemes.

In short, while reworks may result in inefficient processes in renovation projects, urban diseases become worse and urban renewal and urbanization would have to slow down. As mentioned earlier, the lack of original design drawings or the inaccuracy of original building information may be prone to large numbers of design errors, resulting in reworks. Fig. 1 presents the process of applying RE in renovation projects. The rationale is that RE can collect three-dimensional (3D) coordinates of existing buildings needing renovation through advanced scanning technology and accurately restore their original building information into 3D models. Based on the rebuilt digital models, further design analysis can be carried out. BIM data provided by the secondary design model would be used for information management in the subsequent construction and operations and maintenance processes.

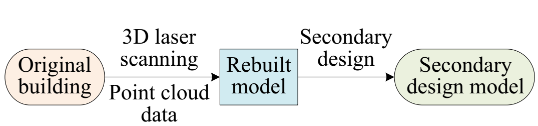

Fig. 1. Process of applying reverse engineering.

2.2. Importance of combining BIM and RE

Measures to reduce reworks should be targeted on enhanced information utilization, which points to BIM implementation. Eastman et al. [20] used BIM to achieve integrated information management in construction projects and made only 0.2% reworks and realized zero conflict between various professional systems. BIM creates comprehensive, reliable, easy-to-access, and easy-to-replace building information for anyone in the entire lifecycle of a building. Grilo and Jardim-Goncalves [21] reported that BIM implementation completely changes project information management mode and can let team members know who is responsible and what obligations need to be fulfilled [22]. Therefore, BIM can maintain information and improve information flow throughout the life cycle of the construction project, which is applied to various fields [23]. Project participants have better access to information and improve the understanding of and control for the project. In addition, the as-built model serves as a knowledge base to record the evolving facility information and allow the facility manager to analyze information about the entire system during the operations and maintenance stage [24].

Nevertheless, an established building information model achieves value only if the data sources are accurate [25]. Regarding renovation projects, the inability to quickly obtain building information or the inconsistency between the original design drawings and the actual buildings will affect the accuracy of the digital model.

This creates the need of using RE to quickly collect a building's geometric information. With help from supporting tools, 3D data of various large, complex, irregular, standard or non-standard entities, and real scenes can be directly generated, thereby facilitating rapid reconstruction of a 3D design model. The collected information can also be used for follow-up processes, such as analysis, guidelines, simulation, display, monitoring, virtual reality, and so on. For instance, El-Hakim et al. [26] constructed a data acquisition system which used a 3D laser scanner and a charge-coupled device (CCD) camera to realize 3D simulation of indoor scenes. Rottensteiner and Briese [27] built a digital surface model using aeronautical laser scanning data and then created a digital terrain model to get building profile by setting height limits. Similarly, Lee and Choi [28] integrated ground-based laser scanning with a digital imaging framework for studying 3D reconstruction of buildings. Stamos et al. [29] created a point cloud data acquisition system that restored a photorealistic 3D model of an ancient building after using the CCD camera to obtain the building objects' color image. Kadobayashi et al. [30] combined terrestrial laser scanning with close-range photogrammetry for the conservation and reconstruction of heritage sites.

In practice, as renovation and modification usually take place after a project's handover and operations and maintenance, changes may not be fully documented. This phenomenon raises difficulties of design and construction in renovation projects as well as increases time and costs. Recently-introduced 3D laser scanners make possible rapid and accurate capturing of a huge number of point cloud data, which produces very dense and elaborate coordinate data points for the surfaces of a physical object [31–33]. Integrating laser scanning with BIM can yield significant advantages over the traditional approaches, specifically by facilitating fast and accurate data acquisition for existing conditions [25,34–37]. With laser scanning, as-built conditions and changes in the operations stage can be documented to ensure the accuracy of information processed in BIM [38].

The combination of BIM and RE in the architecture, engineering, and construction (AEC) industry was also explored in previous studies. By combining BIM, 3D laser scanning, and radio-frequency identification technology, Hajian and Astani [39] studied real-time information management of construction projects. Huber et al. [40] automatically generated an as-built model based on laser scanning data. Giel and Issa [38] studied how scanned data could be used for analyzing an existing building information model to assist quality control. Wang et al. [25]

achieved automated quality assessment of precast concrete elements with geometry irregularities using terrestrial laser scanning and BIM. Based on the above analysis, this study would combine BIM and RE in the proposed framework for renovation projects in urban renewal.

2.3. Importance of combining BIM and VR

VR is a computer technology that gives users an illusion of being immersed in a virtual environment. Fundamentally, VR enables a computer simulation of real situation where human subject may interact with the virtual environment [41]. This technology generates visualizations of spatial data that can be interactively controlled by the users and displayed on a screen [42]. It has many applications within the AEC industries [43–45].

Hall and Tewdwr-Jones [46] highlighted communication difficulties among different stakeholders, which were mainly resulted from insufficient collaboration and information sharing in the project life cycle. Nevertheless, with VR, a new solution has emerged. Bouchlaghem et al. [43] reported that VR offers an efficient communication and construction platform which can freely navigate through 3D scenes from a first-person perspective, facilitating a better understanding among all involved parties, despite their professional expertise or backgrounds. While the use of VR itself has not been widespread due to the lack of required 3D data in renovation projects, the combination of BIM and VR has created new possibilities. Specifically, 3D data can be extracted from the virtual design environment, instead of being created from scratch using two-dimensional (2D) plans, elevations, and sketches as references. In the past, field workers and engineers often needed to supervise or perform construction activities by reading annotated design drawings, manuals or photographs, which consumed a considerable amount of time and efforts. As a comparison, the combination of BIM and VR ensures the field staff in a renovation project, especially those with limited experience of using traditional design documents, to better understand what the designers mean, efficiently expedite construction activities, and thus avoid reworks. This enables the field personnel to visualize design models with detailed objects and properties, especially those complicated ones, directly on-site right before construction. Furthermore, the design database will automatically update any changes and generate all representations and visualization for these site staff, avoiding any misunderstandings and allowing for a thorough understanding of the changes' construction impacts [11,47].

2.4. Importance of incorporating advanced supporting tools derived from the manufacturing industry

In addition to the aforementioned concepts and technologies, this study also described some supporting tools that would be used in the construction industry, including WBS, PC, and 3D printing. Andresen et al. [48] advocated that the most important idea of Britain “Construction IT, 2000” research program was to learn from the manufacturing industry. In 1962, the United State Navy first proposed WBS in project management of modern ship [49]. The Project Management Institute (PMI) defined WBS as “a deliverable-oriented grouping of project elements, which organizes and defines the structure of the entire project, with each descending level representing an increasingly detailed definition of the project work” [50,51]. WBS defines a project's scope and forms the foundation for planning, responsibility assignment, budgeting, and information management. García-Fornieles et al. [52] noted that WBS was probably the most valuable and indispensable tool for project management. By partitioning a project into stages, deliverables, and work packages, a systematic WBS can search pivotal work and reduce unwanted possibilities while providing effective project management in the planning process. Thus, the correct use of WBS paves the way for effective planning, estimating, monitoring, and scheduling of activities [53,54]. In construction projects, the difficulties of delivering on time, within budget, and to required quality standard face every project manager. WBS is one of the tools available to aiding project planning and management. In particular, project engineering is systematically decomposed into smaller and manageable units to effectively control the construction phase and reduce reworks.

Moreover, in the traditional project delivery, the design and construction phases are fragmented, resulting in a less coordinated workflow. In a construction project, very often the design was not completed until the construction phase where construction and installation activities already commenced, so design errors were not found until then. Consequently, unnecessary changes and reworks occurred, consuming time and resources. The idea of PC originates from the manufacturing industry, with buildings expected to be built in the same way as a car or a piece of flat-packed furniture is assembled [55]. In a project using PC, the entire industrial value chain is integrated with standardized design, component parts, and mechanized construction. This saves labor, speeds up the progress of the project, and reduces wastes [16].

Furthermore, the evolution of 3D printing has changed design, engineering, and manufacturing processes across industries such as aerospace, consumer products, and automobiles [56]. After the design phase, the 3D printing technique can be used to produce a building's prototype model to assist the project team in the visual management in the construction and operations and maintenance phases. Specifically, the prototype model helps the primary participants to check whether the design meets relevant functional and aesthetic requirements.

Although the technologies and tools mentioned earlier have drawn great attention from researchers and practitioners in the construction industry, currently they have not been popular enough to maximize their values in renovation projects. The combination of BIM and RE, with support from 3D laser scanning, VR, as well as supporting tools derived from the manufacturing industry may be a valuable way for project management in renovation projects, because this provides a holistic view of using the state-of-the-art innovations in the renovation process. Despite the significance and repercussions of the technical solutions, previous studies tended to only illustrate the advantages of these independent technologies in projects, the integration of BIM, RE, and their supporting tools in the construction industry, especially in renovation projects in urban areas, has not been fully explored. Therefore, the aforementioned digital construction framework needs to be developed to fill this gap.

3. Methodology

This paper was divided into three stages. Firstly, a literature search was carried out to establish the need of integrating BIM and RE, incorporating other supporting tools, as well as learning from the manufacturing industry for reworks reduction in renovation projects during urban renewal. Secondly, a digital construction framework was developed to demonstrate how project teams may enhance information and organization management in renovation projects. BIM, RE, and other advanced tools reviewed were used in this framework. Finally, a case study was conducted to validate the proposed framework. For better readability, the methods of data collection and data analysis would be reported in the “Case study” section.

4. Development of a digital construction framework for renovation projects

Under WBS's guidance, this study proposed a comprehensive framework for effective information and organization management, which integrated BIM, RE, and other supporting techniques such as 3D laser scanning and PC. The framework was described in the life cycle of renovation projects, namely the planning, design, and construction phases, as shown in Fig. 2(a). To keep work manageable in a renovation project, WBS and MBS are applied for the primary participants to control the project. The framework is able to provide information for optimizing the organization, cost, contracting, quality, time, and so on.

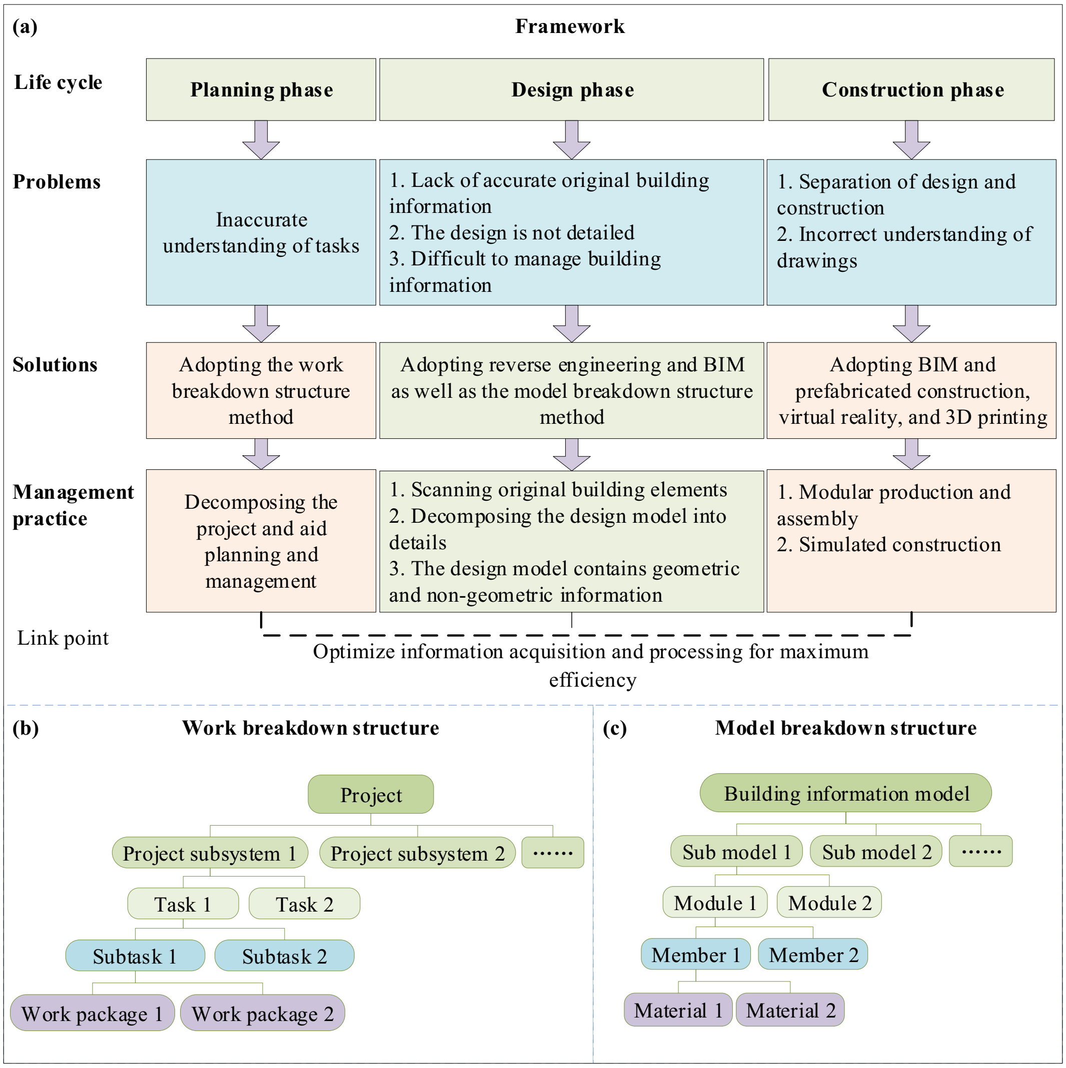

Fig. 2. Proposed framework for implementing digital construction in renovation projects.

The subsequent sections would explain in details the structure and contents of the solutions provided in this framework as well as the basic rational behind them.

4.1. Planning phase

In an effective construction process, information needs to be delivered to the right person at the right time. In a renovation project, WBS aims to ensure comprehensive and proper definition of all the work as well as accurate information rebuilding and transmission among the primary participants. In the WBS process, project objectives are firstly defined, focusing on products, services, and results provided. As shown in Fig. 2(b), in a WBS, the highest level represents the entire project, which is then subdivided into smaller elements, representing the next level in the hierarchy. The deconstruction process continues until the project has been sufficiently decomposed to acquire effective project control. After deconstruction, all sub work appear once in the WBS and are independent with each other. Eventually, the lowest level refers to work packages, representing that each small task has been assigned to an individual, department, or organization [57]. With WBS, the complexity of the project's tasks is reduced as they are broken down into deliverables (such as building components), which reaches a manageable size. The tasks with specific and expected durations, resources, and costs are manageable and controllable. The method can define project work in details and provide a clearer idea of estimated duration, cost, and resource requirements. In the planning phase, the WBS process shows the whole picture of the renovation project, helps the major participants understand their roles and responsibilities, such as who should be responsible of getting 3D coordinates of the original building, and establishes a visual project deliverable to estimate workloads. This process makes sure that the participants can take full advantage of their talents and insights and collaborate at the later phases of the project to create the largest value for the owner.

4.2. Design phase

In the design phase, this framework should ensure that users can acquire accurate building information from the existing building needing renovation. RE is adopted for this purpose. It is a reproduction process of a product's design that uses reverse analysis and research. The use of 3D laser scanners would assist the users in rapidly and accurately fixing targets and capturing elaborate coordinate data points of the existing building's surfaces. Specifically, by collecting, splicing, and processing the point cloud data of the original building, the engineers acquire accurate building information. The data obtained from the 3D laser scanners reduces the design team's reliance on the traditional 2D drawings to establish its 3D design model.

Following this, the collected point cloud data are then used to model the building, or restore its design model in a virtual design environment. This model redevelopment process paves the way for subsequent secondary design. The composite design model covers both geometric and non-geometric information (such as bill of materials) of the existing building, such as types of materials, facilities, and so on. Thus, the integration of RE and BIM can effectively avoid the inconsistency between the original construction drawings and the real world building which is caused by poor construction quality, construction deviation, or uninformed design changes.

MBS is used to assist in the design modeling process and the secondary design process. According to the same principle established in the WBS process, a MBS determines a clear scope of the composite design model and deconstructs it into smaller and manageable modules to make quality and cost under control. As shown in Fig. 2(c), to meet the specific needs of different participants, MBS decomposes the design model until detailed materials (such as a screw on the door) are designated to respective staff, which clearly shows the overall picture of the existing building without leaving out any details. The information model contains all the information needed during construction, whereby the renovation activities of the building can be carried out.

4.3. Construction phase

As mentioned earlier, the communication difficulties between the designers and site staff would inevitably produce mistakes and reworks during the construction and installation process. To improve the efficiency of information exchange in this renovation project, the application of other technologies in the construction phase carries critical implications. Traditionally there were weak or even no linkages between design and manufacturing work. The manufacturing work needed to re-enter and process design data, resulting in inconsistencies in design and manufacturing information. Thus, the traditional workflow was not well coordinated due to the separation of the design and construction phases, creating mistakes in design and reworks in the actual construction and installation phase. Consequently, changes that should have been enabled in the design phase occurred in the later phase, eventually consuming extra time and resources.

As shown in Fig. 2(a), the combination of BIM and PC may be a solution [5]. With BIM, the secondary design team can design for manufacturing and assembly [16]. PC is a manufacturing process that takes place in a specialized facility where various materials or discrete elements are joined together to form a component for final installation.

The combination of BIM and PC makes the 3D solid design model the only basis in the manufacturing and installation process, which changes the traditionally fragmented design and construction phases. The Digital Product Definition Data Practices ASME Y14.41-2003 standard advocates making full use of expressive force in 3D models to explore more efficient and comprehensible information expression. Thus, both BIM and PC eliminate the use of 2D drawings and ensure the uniqueness of the design data. The combination is an ingenious application of information technology and industrialization, which saves labor, speeds up the renovation project's progress, and reduces wastes.

Moreover, VR enhances overall design communication and digital construction. Specifically, in the design phase, the combination of BIM and VR allows the project team, especially the owner, to evaluate in person the materials and lighting in the building for further design improvement. During construction if the on-site workers are immersed in an interactive virtual environment which is created by the designers using BIM and VR, the workers would better understand design intent. Besides, responses to safety incidents simulation and measures of addressing construction difficulties are previewed using VR. The combination of BIM and VR creates animations, showing the fastest sequence and process of construction and assembly. If there is anything wrong with the sequences of building components installation or the connections among the components (especially those with complicated geometries), the animations can clearly show such problems whereby the team can adjust accordingly before actual construction. The process helps the site workers who lack a professional understanding of traditional design drawings and assembly quality. This combination greatly improves the efficiency of construction. Thus, the importance of VR in the construction phase cannot be overemphasized.

Furthermore, 3D printing is also used to help improve the site staff's understanding of the design intent. Specifically, the project team can use this technique to produce the prototypes of building components from the design model. This shows whether the components achieve relevant functional and aesthetic standards in a very intuitive way. Thus, 3D printing can not only help the designers further optimize the design but also provide a clear understanding for the site experts.

5. Case study

5.1. Background of case project

To explore how the proposed framework could be applied in renovation projects, this study took Haimian Mission Hills international shopping center, for example, which was located in Mission Hills Haikou, Hainan, People's Republic of China. The project was a commercial complex needing renovation, with a construction floor area of about 50,000 m^2. This project was invested by Hainan Duty-Free Goods Co., Ltd. and Mission Hills Group and the total investment was about 960 million RMB. The renovation project began in December 2015 and was completed in July 2016. The materials used in this project included polytetrafluoroethylene, ethylene tetrafluoroethylene air pillow membrane, and 3200 tons of steel. The difficulties facing the project team were: (1) the schedule of design, procurement, and construction was tight; (2) the form of contracting agreement was Engineering, Procurement, and Construction (EPC); (3) the investment budget was tight; and (4) the financing structure was a joint venture.

The EPC contractor (Company A) undertook the design, procurement, and construction work, which followed the proposed digital construction framework. This company was well qualified as it possessed experience both in the manufacturing industry and the construction industry. Thus, the Haimian Mission Hills international shopping center could well serve as a case project.

5.2. Data collection and presentation

To evaluate the validity of the proposed framework, personal interviews and investigation were performed to obtain feedbacks from professionals of Company A. The interview questions focused on the implementation process and the results of Haimian Mission Hills international shopping center. Overall, there were five AEC professionals in this company who were knowledgeable about the project practices and had actively participated during the execution of the renovation project. Among which, four (80%) agreed to participate in the interviews. In order for these experts to provide insights, semi-structured interviews were undertaken, maximizing the flexibility of the interviews. The interviews were conducted face to face, which was convenient for clarifying ambiguous questions and observing the actual situation of the renovation project. During each interview, an interview guide was used to maintain the direction of the conversation while probing into issues of interest. Specifically, the objective of the study was explained to the experts. Then, they were requested to provide information about the project. Finally, the experts were invited to comment on the proposed digital construction framework and its use in this renovation project. The durations of the interviews ranged from 40 to 60 min, with an average of 50 min. All the interviews were recorded and transcribed. The answers provided by the four experts were consistent.

The profile of the four interviewees was presented in Table 1. All the respondents had more than five years' experience in implementing BIM and RE. Although company A was not a large firm, it was leading in the field of RE and BIM implementation. Besides, the four interviewees accounted for 80% of the available AEC professionals in this company

Table 1
Profile of the interviewees in the EPC contractor.

Interviewees	Work experience in BIM and RE	Duties
1	10 years	Project management
2	9 years	BIM consultancy and project management
3	8 years	Mechanical, electrical, and plumbing design
4	6 years	Architectural and decoration design

who participated in the whole process of the renovation project. On the other hand, previous construction management studies used similar numbers of experts for validation purposes. Specifically, Liu and Ling [58] used one expert with three cases for verifying a proposed system. Arain and Low [59] used four professionals with one case to validate a proposed system for managing variation orders. Thus, considering the actual circumstances of the case project, the number of interviewees was considered adequate for validating the proposed framework. Hence, the collected data was considerably reliable and accurate.

5.3. Application of the proposed digital construction framework

With the use of the proposed digital construction framework, all project-related information flowed smoothly throughout the processes and the project's progress was effectively controlled. The project was divided into three parts, namely outdoor canopy, mushrooms of central square, and interior design (see Fig. 3). Among which, the most difficult one was the renovation of the outdoor canopy, which was actually simple shelters supported by steel columns before being renovated. The outdoor steel structure canopy had a construction floor area of 17,000 m^2 with a height of 32 m, and included nine areas. In the beginning, the designers broke down the life cycle work of the outdoor canopy using the WBS method, as shown in Fig. 4. From a macro perspective, the project life cycle included seven phases (preliminary planning, planning and design, design, contract, construction, completion, operations and maintenance).

The work in each phase was further decomposed. In particular, the planning and design phase was divided into 11 tasks. To assign the tasks to specific staff, some tasks were subdivided until smaller manageable ones were reached. For instance, “climate analysis” was divided into sunshine analysis and wind power analysis. In the design phase, there were seven tasks including “construction of ditch system”, “lightning protection grounding system”, “bird driven system”, “floodlighting system”, “fireproof coating”, “inflatable equipment”, and “reinforcement of the original building structure”.

After the work breakdown analysis, the designers started to build an integrated building information model of the outdoor steel structure canopy which needed renovation. Firstly, an outline was drawn to clarify the sequences and details of the model which included nine parts (see Fig. 5). The work involved the establishment of the original building model and secondary design. The former applied RE to restore a model for the original building, and the latter was to design for renovation based on the re-built model. Therefore, taking the first part for example, the model of the site original building and civil structure part was divided into the original building structure drawings, curtain wall drawings, as well as municipal and landscape planning drawings. Then, the original building structure drawings were further decomposed into structural columns and beams.

After completing the above process, the application of RE enabled accurate on-site point cloud data collection and avoided any adjustments caused by inconsistencies between design and construction. In this study, the Trimble TX5 high-speed 3D laser scanner was used. Through high-speed laser scanning, the designers had fast access to the 3D coordinate data of the measured objects so that they could rapidly establish targeted 3D point cloud model according to the collected data (see Fig. 6). The scanner could measure on 976,000 points per second and up to 120 m. Compared with conventional measurement means, this measurement means saved a lot of time and labor costs. Besides, the 3D laser scanner also incorporated a color camera that could provide up to 70 million pixels. Consequently, fine photos and 3D color images were obtained in millions of measurements (see Fig. 7). This way greatly improved the measurement efficiency and saved a lot of deepening and checking time for the design phase. Following this, the BIM model of the original building was developed by the SolidWorks

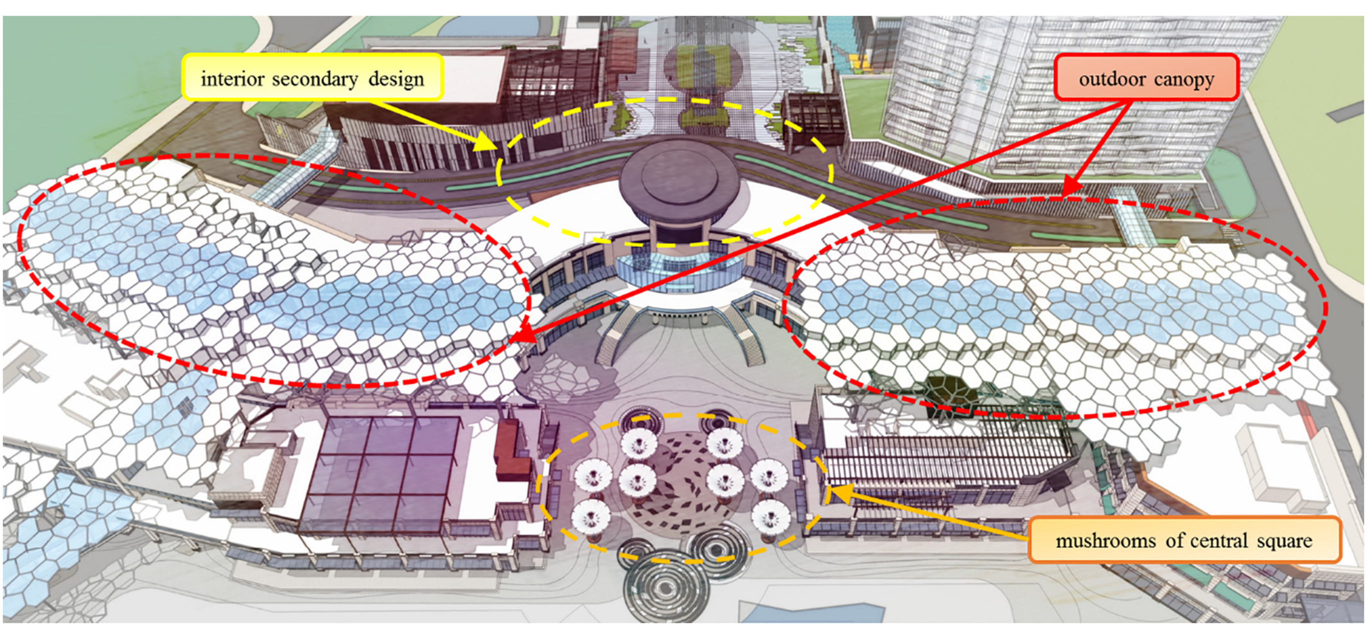

Fig. 3. Haimian Mission Hills international shopping center in Hainan.

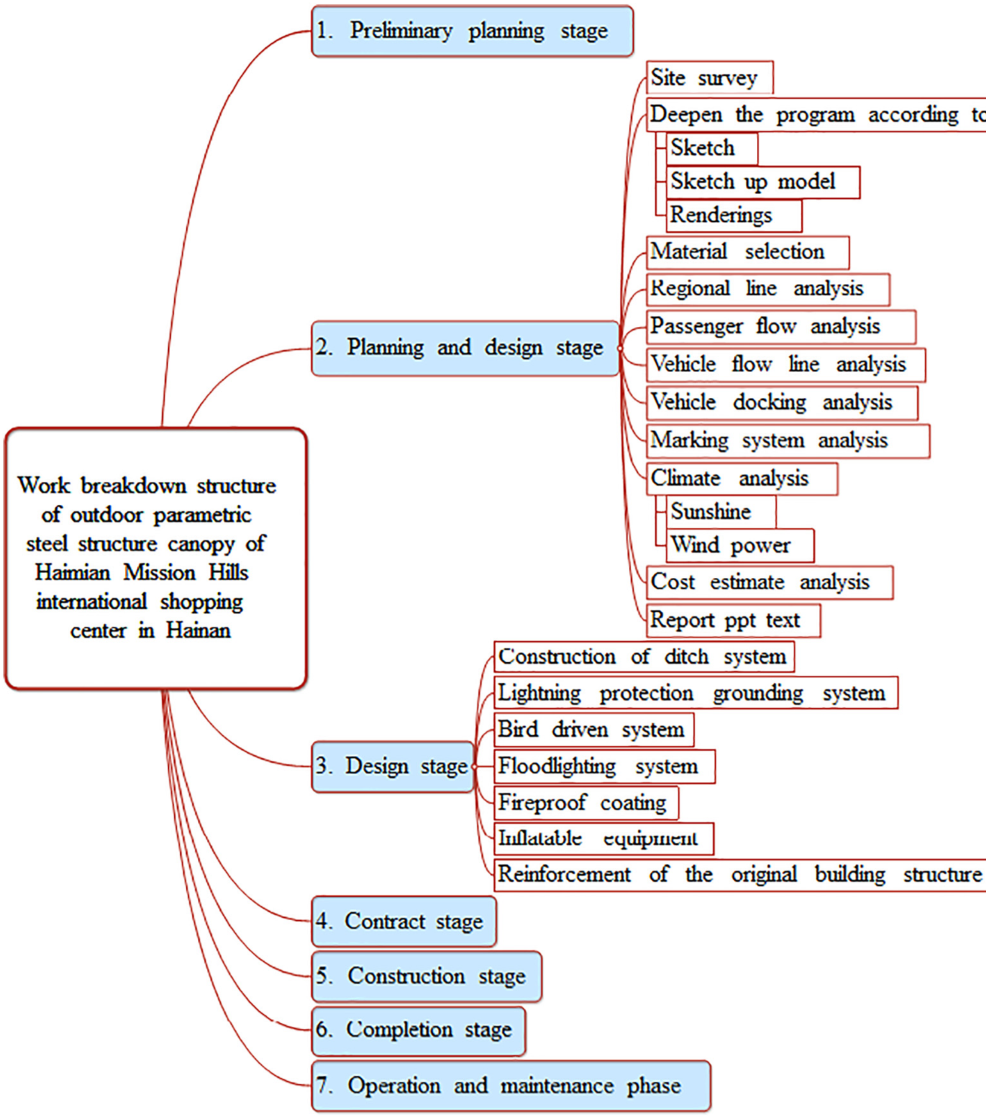

Fig. 4. Work breakdown structure of outdoor steel structure canopy.

platform based on the point cloud model.

Subsequently, the structural columns of the steel structure canopy were aligned with those of the original building structure drawings, as shown in Fig. 8. After importing the BIM model into 3D3S, a structural analysis was conducted to ensure that the steel structure of the canopy met relevant safety requirements (see Fig. 9). Through optimization, the maximum stress values of the steel columns under different conditions were extracted after iterative calculations and adjustments. The values were compared with those of the columns of the original building structure so that a secondary reinforcement design could be done on the parts which did not meet demand. Moreover, the canopy's steel structure components were decomposed based on the BIM model for the purpose of digital manufacturing. This model automatically generated high-precision data files that could be directly sent to manufacturers to place orders. The digital manufacturing could reduce material wastes, as shown in Fig. 10.

After fixing the design, 3D printing technology was used to rapidly make a prototype model of the canopy's steel structure. As shown in Fig. 11, this prototype helped the EPC contractor visualize the final production and thus verify the overall design of the canopy in terms of its functional and aesthetic values. Besides, the prototype model could also assist the management in the construction and operations and maintenance phases.

During the construction phase, due to limited construction space, the assembly area could only be arranged within one-kilometer radius around the construction area. The building information model was used to simulate the construction site layout to ensure that the unit module could be transported from the assembly area to the construction area. Considering the original building structure, for example, the model could simulate the tower crane's cantilever position on the construction site to ensure that the entire construction area could be covered. As shown in Fig. 12, this process also facilitated the selection of tower cranes, with specified equipment, and the preparation of relevant special construction programs.

The combination of BIM and VR created installation animations, which could assist the site workers in visualizing and understanding the process of assembling the building components, such as tree structure assembly, monolithic hexagonal assembly, and hexagonal grid assembly (see Fig. 13). This process made project communication and decision-making more efficient. Specifically, it provided the site workers an intuitive understanding of how to correctly assemble the steel structure in a proper sequence. As a comparison, traditionally this process could only be done by imagination of the positions and sequences of the building elements. This process would inevitably produce mistakes and reworks, because the construction workers needed to spend much time repeatedly reading and identifying respective

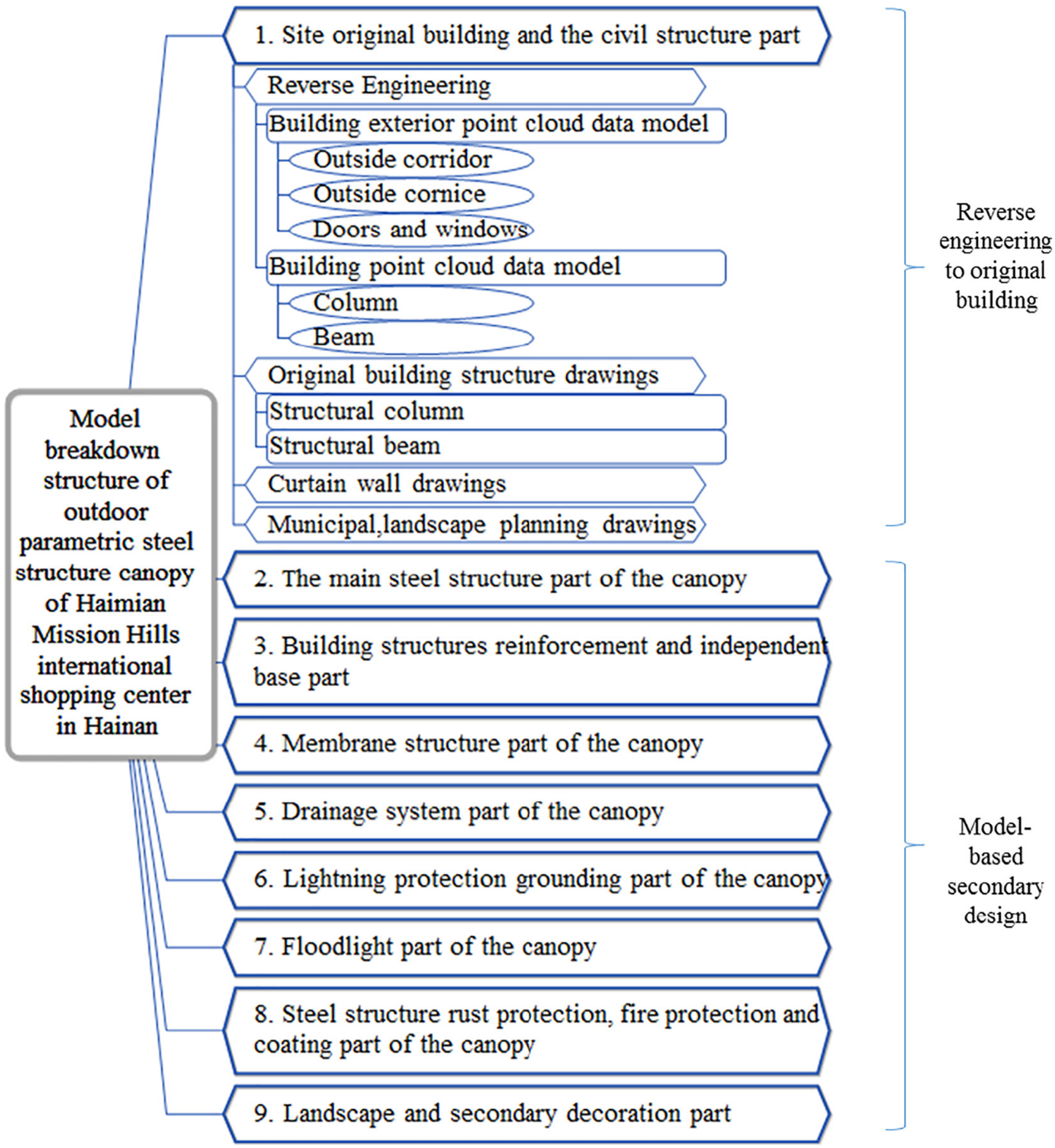

Fig. 5. Model breakdown structure of outdoor parametric steel structure canopy of Haimian Mission Hills international shopping center in Hainan.

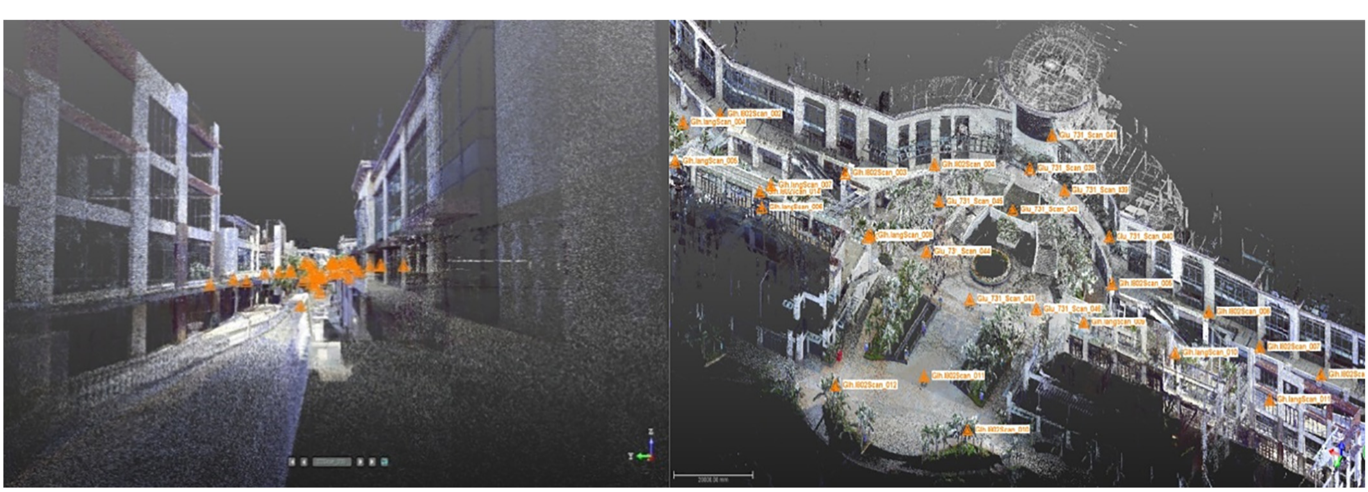

Fig. 6. Point cloud data model.

Fig. 7. Example of three-dimensional color images of site data collection.

drawings. Any information transmission distortion would cause huge losses. However, with the help of VR, the design options were virtually simulated, which reduced potential misunderstandings. Finally, after the renovation construction, the design and construction information was saved and stored in an as-built model for operations and maintenance uses. Because the shape of each canopy was different, it was hard to learn from previous projects to install this canopy. Thus, the combination of BIM and digital production was valuable because it could easily replace or renovate a broken canopy.

6. Results and discussion

The performance of implementing the proposed digital construction framework in the outdoor canopy of the case project was presented in Table 2. The interviewees from the EPC contractors reported that if using the traditional way, the estimated construction duration of renovating the steel structure canopy would be 10 months and the renovation project would cost 133.70 million RMB. As a comparison, the use of the proposed framework actually lasted eight months and 123.80 million RMB was spent, saving 20.00% and 7.41%, respectively. Besides, the time spent in estimating the project cost was reduced by more than 50% and the percentage error of this estimation was less than 3%. In addition, the project management cost was saved by more than 40%.

Meanwhile, all the four interviewees reported that the difficulties in design and reworks reduction were the most important problems. Thus, other benefits were also reported. Regarding the canopy, the overall benefits to the owner, according to the EPC contractor, included: (1) efficiency of the whole renovation process was optimized by 15%; (2) design changes were reduced by 30%; (3) collisions among pipelines were identified and removed and the relevant cost was saved by 10%; and (4) reworks were reduced by 25%. These results indicated that the proposed framework was validated in the real-life renovation project and could greatly improve the effectiveness of renovating existing buildings during urban renewal.

The enhanced performance was analyzed and discussed. The efficiency of renovating a building depends on two key factors, namely information acquisition and processing. When construction activities proceeded with RE, the accuracy of the re-created design model and respective drawings could be improved, which minimized the design changes. This was consistent with Wang et al. [60] which used colored laser scan data for fast and accurate 3D modeling and automated position estimation. However, in this previous study the experts in the field of BIM and laser scanning did not incorporate other techniques such as WBS which determined the details and sequences of the

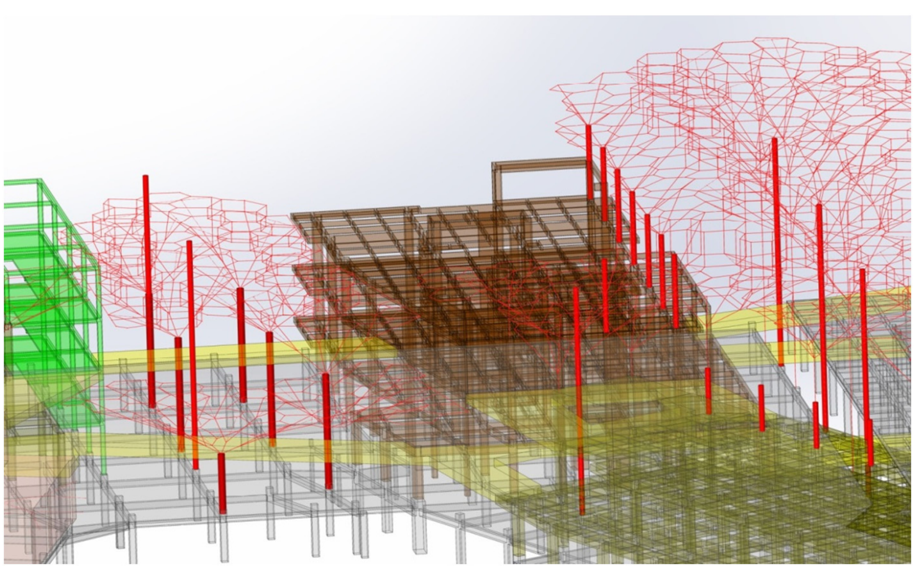

Fig. 8. Alignment between steel columns of canopy and those of original building.
(Note: The red columns were new steel columns to support canopy and the white ones represented those previously used in original building)

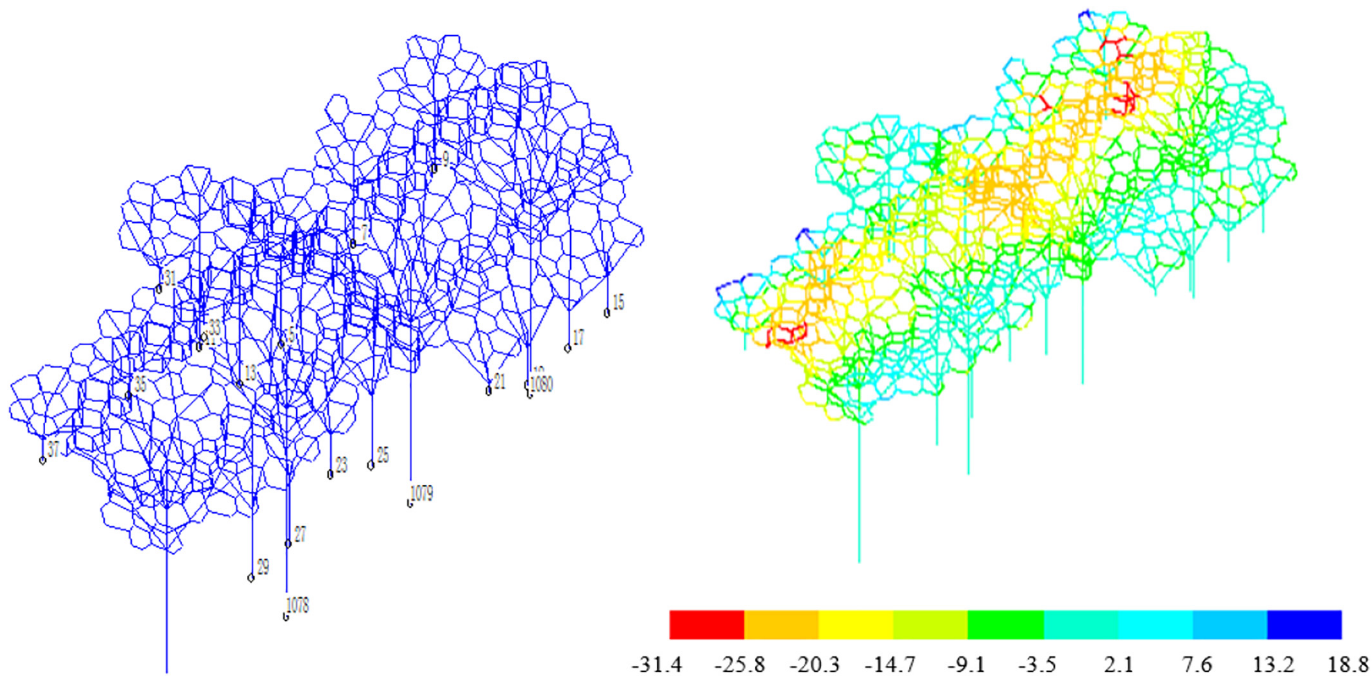

Fig. 9. Structural analysis results.

renovation work to further improve the case project's efficiency. Since the secondary design was complicated, optimization measures such as MBS could be applied so that the progress of the design work could be accelerated. The proposed MBS approach by the EPC contractor demonstrated the sequences and details of the design model. Moreover, the reduction of reworks also relied on the accuracy of the preceding design work and the processing of the preceding construction activities. Integrating BIM and VR provides the site workers a deep understanding of the drawings to improve the installation accuracy.

Furthermore, this proposed digital construction framework is

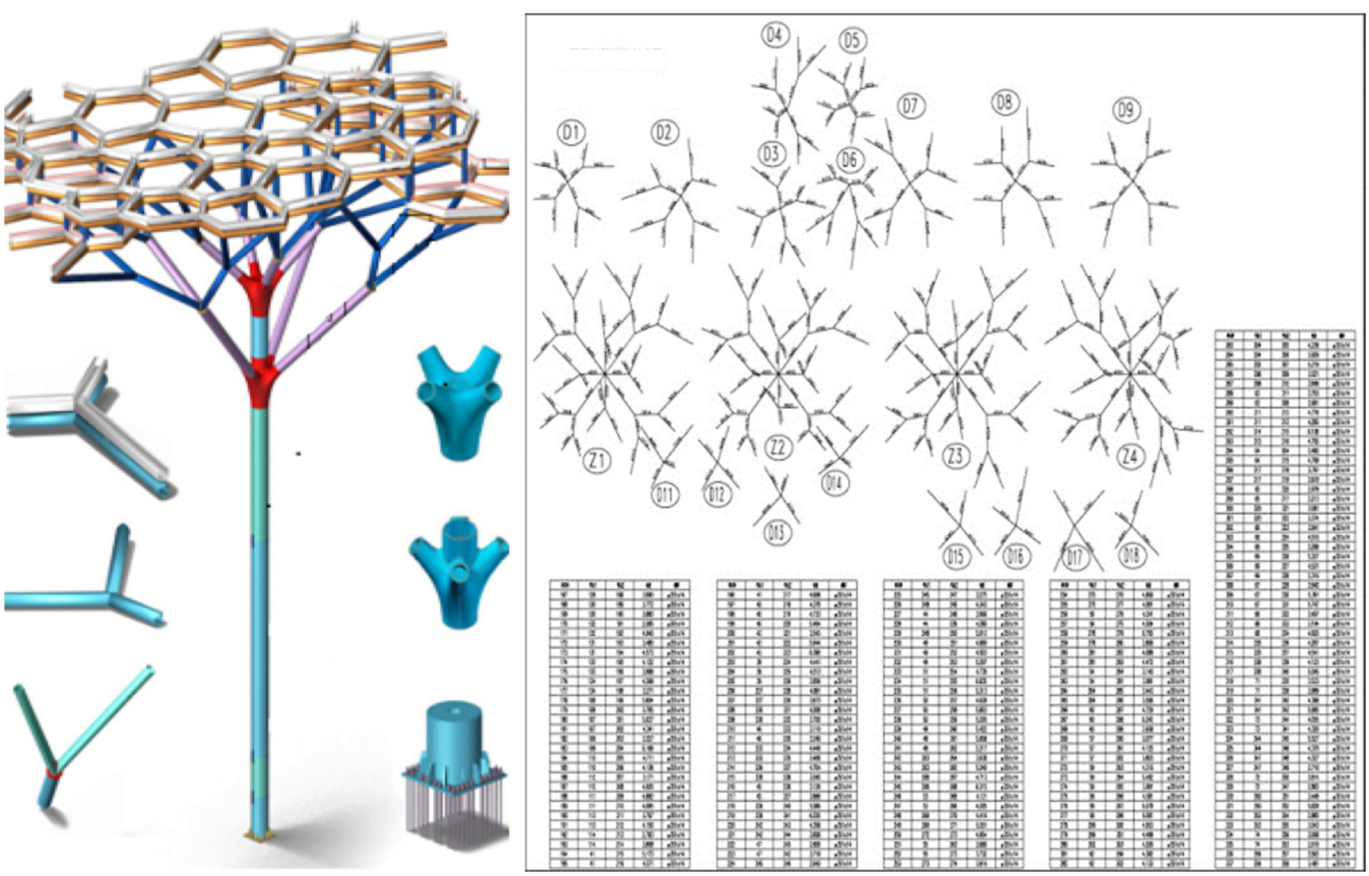

Fig. 10. Sample model of steel structure and its bill of materials.

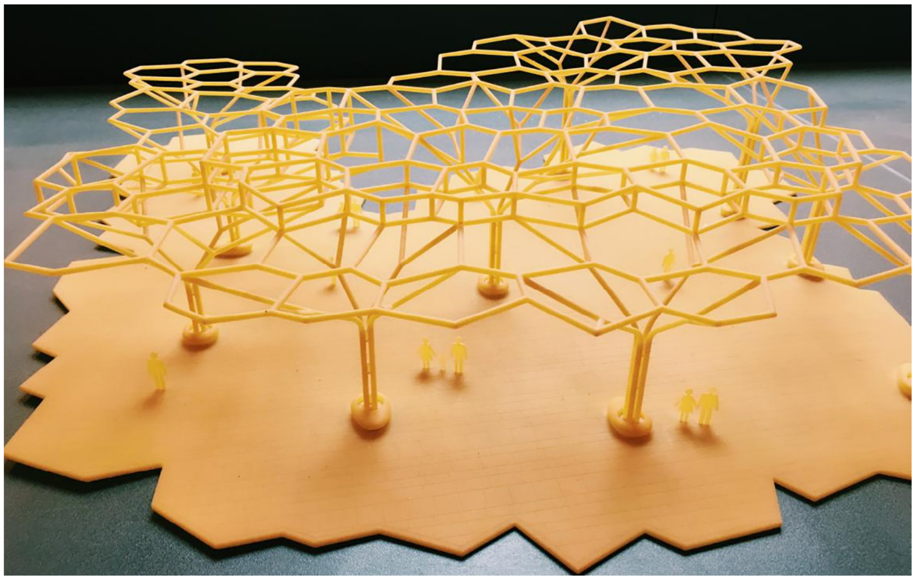

Fig. 11. Prototype of outdoor canopy's steel structure using 3D printing.

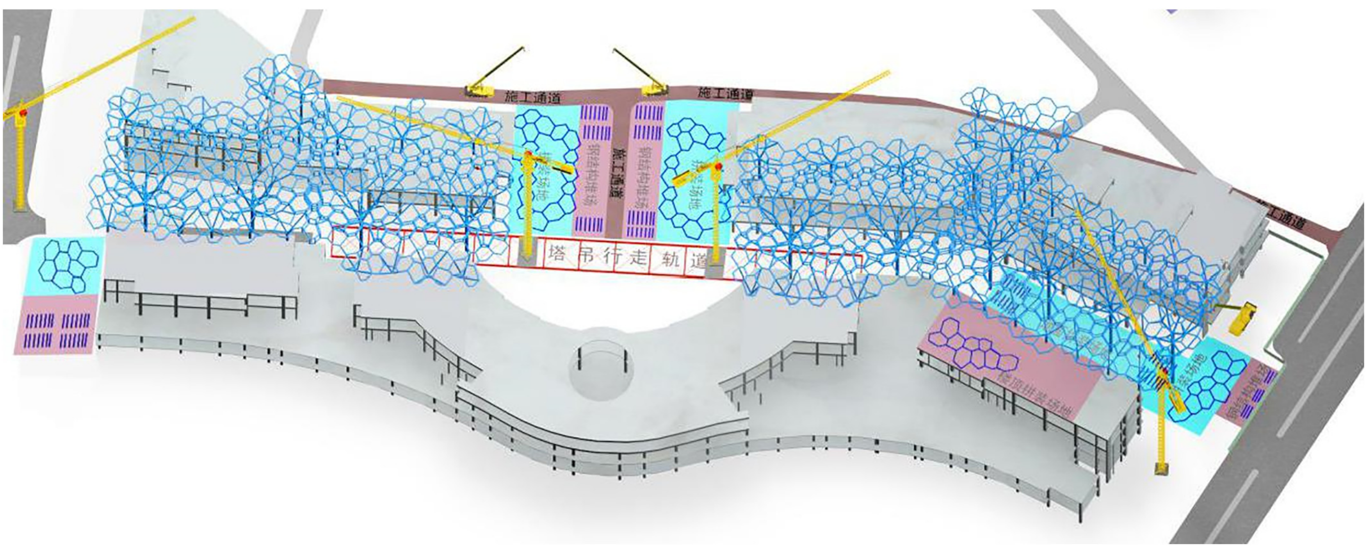

Fig. 12. Canopy construction simulation.

universal for renovation projects and the pattern of using these advancing technologies can be duplicated in other buildings needing renovation. In particular, the EPC contractor (Company A) had been using this framework in other renovation projects and eventually achieved significant improvements in controlling cost, duration, reworks, and other metrics. In addition, no such frameworks have been established in the literature. Thus, this paper provides a clear framework for renovation projects, especially those adopting design–build or other fast track approaches, expanding the literature related to BIM, RE, and urban renewal.

7. Conclusions and recommendations

This study explored an innovative way of improving the efficiency in renovation projects during urban renewal. Through the literature review, inefficient construction processes were investigated during the renovation process, which created large numbers of errors, changes, and reworks. Following this, this study proposed a digital construction framework. Learning from the manufacturing industry, the primary technical solution was to combine BIM and RE under the guidance of WBS, which was supported by 3D laser scanning and MBS in the planning and design phase as well as VR, 3D printing, and off-site fabrication in the construction phase. Besides, the applicability of this proposed framework was tested and validated in a case study of a renovated international shopping center in Hainan, China.

The main findings and solutions were summarized. Firstly, the combination of BIM and RE technologies improved the information utilization among all the professionals in different phases. In particular, the accuracy of the original building information was essential to the secondary design in this renovation project. Therefore, the original building structure was restored based on the 3D coordinates data collected by 3D laser scanning. Secondly, according to the secondary design model, it was still difficult for the site workers to understand the design intent and determine installation positions. Combining BIM and VR could help the workers better understand the design and construction intent. In the interviews, the field experts also reported that the effective use of BIM required PC to make the 3D solid design model the only basis in the manufacturing and installation process. In addition, another important issue was to have an overall picture of the lifecycle work and deliverables. This required that the management staff of the

Fig. 13. Canopy installation simulation using virtual reality.

Table 2
Performance evaluation of applying the proposed framework in the outdoor canopy.

Canopy renovation	Traditional mode	Proposed framework implementation mode	Saving
Construction duration	10 months	8 months	20.00%
Total cost (million RMB)	133.70	123.80	7.41%

planners and designers knew the key points, measures, and roles during the project life cycle. Therefore, WBS and MBS were adopted to assure enhanced organization and management quality. Overall, the combination of BIM and other technologies is a mainstream activity in the construction industry, especially in the wave of urban renewal. It was expected that this digital construction framework integrating BIM and RE for renovation projects would form the foundation of the rapid development of urban renewal in city areas.

Despite the achievement of the research objectives, the proposed framework has a limitation, namely the compatibility of software. Different parties in a renovation project tend to use different software applications or software versions available to them. Nevertheless, to effectively use the framework, the project team can align the primary participants from the beginning to ensure project-wide data interoperability [5], or alternatively, an EPC contract can be used. In addition, overseas project teams may also apply the proposed framework because the technologies or technological processes used in this study are widespread in the global construction industry [60,61]. Future research would continue to measure the applicability of the proposed framework in other construction sites. More exact figures would be collected to investigate the efficiency of renovation projects and the effectiveness of this framework.

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