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Quality Control of a Complex Lean Construction Project Based on KanBIM Technology

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ABSTRACT

In developed countries such as Europe and the United States, building information modeling (BIM) technology has become an indispensable tool in the construction industry. In recent years, it has also contributed to a tide of reform in the construction industry in China; BIM technology has gradually been applied to large, complex projects and has become indispensable to lean construction. Based on BIM and lean theory, this study establishes a KanBIM quality control (QC) system to achieve a more efficient QC process by analyzing the tools and technologies necessary for the system. The research results have practical significance; they can contribute to improving the quality of construction enterprises, reduce project costs, and enrich the lean QC theory and advance BIM education and implementation in the construction industry.

Keywords: construction quality control, human-computer interaction, integrated project delivery (IPD), Kan building information model (KanBIM), lean construction

INTRODUCTION

At present, the construction industry is considered one of the most important industries in China, supporting the country's economic growth. However, it has been difficult to standardize the management of the construction industry due to its inherent features, namely, complex technologies, overloaded practitioners, and the challenges of large-scale projects. With the improvement of China's economic strength, large-scale construction projects continue to emerge. Owners and construction management companies focus on progress, cost, quality, and safety. However, due to conflicting interests, the quality of many projects cannot be guaranteed after completion; significant quality problems and security risks sometimes occur after project acceptance. Therefore, many researchers are concerned about how to enhance the quality of projects while ensuring control of project costs and maintaining progress. The popularity and successful application of information technology in other areas of business have brought new technical impetus for the transformation of the construction industry. Many researchers are committed to the application of computer technology in the construction industry and have proposed concepts of virtual design and construction, building information models, and visual construction (Eastman et al.2011).In some developed countries, such as Europe and the United States, building information technology has been applied to practical engineering and has effectively improved the efficiency of project construction and the level of project management. This is considered an important turning point in the transformation of the construction industry.

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State of the literature

- Many researchers have been committed to the application of computer technology in the construction industry, and the concepts of virtual design and construction, building information model, and visual construction have been proposed.
- A number of researchers have enriched the theoretical basis of lean construction and proposed means and methods to support lean construction, making lean construction a basis of theoretical and innovation support in the building industry.
- From the studies of the above scholars, it can be seen that the study that integrates BIM technology and lean construction theory still lies at the initial stages.

Contribution of this paper to the literature

- Based on BIM and lean theory, this study establishes a KanBIM QC system to achieve a more efficient QC process.
- Research results of this study have a certain practical significance, it can contribute to improve the quality of project construction enterprise, reduce the project cost, and further improve and enrich the lean QC theory.

Nevertheless, the development of construction information technology in China is still in the initial stage, the scope of application is relatively limited, and the actual application system is still immature.

In the 1980s, the concept of lean production was raised by the International Automotive Project group at the Massachusetts Institute of Technology, which was studying new production methods that were successfully used in Japan by Toyota. "Lean thinking" aroused the interest of many experts and scholars. Koskela presented the concept of "lean construction" at the first meeting of the International Group of Lean Construction (IGLC) (Koskela, 1992), which set out the idea of applying lean production ideas to the construction industry. By analyzing the similarities and differences between building production and traditional production and the uniqueness of the construction field, Koskela's report believed that lean thinking, which was successful in the manufacturing industry, had the potential to transform the construction industry. At the same meeting, Ballard proposed the Last Planner System (LPS) (Ballard, 1994; Ballard, 2000). Following this, many scholars conducted in-depth studies and continuous improvement on the LPS, making it an important management tool to achieve lean construction (Formoso & Moura, 2009). Sacks et al. analyzed the implementation requirements of BIM-based lean production management system from the process, product, and method of visualization, including "pull" workflow control and stability maintenance and continuous improvement systems, to build the process framework of the KanBIM planning and control system, with verified results (Sacks, Treckmann, & Rozenfeld, 2009). Shou et al. proposed a method that integrates operation and maintenance management, BIM technology, and lean theory based on the current situation of a project and the insufficient application of BIM technology and analyzed its operational process and results in practical cases (Shou, Wang, & Wang, 2014). Sacks et al. analyzed the construction visualization techniques that support lean construction, explained the implementation and the actual effect of the method when combined with process visualization and "pull" workflow control theory, taking the visual tool of two specific workflows as an example (Sacks, Koskela, Dave, & Robert, 2010). Sheriz and Patricia analyzed the synergistic effect between LPS and BIM technologies and explored whether better workflows could be obtained by applying a BIM-based weekly planning model in two projects (Sheriz & Patricia, 2014). Laine et al. studied how to improve the efficiency of information transmission, combining visualization control and BIM technology, and proposed that a standardized model view (SMV) could effectively promote lean construction (Laine, Alhava, & Kiviniemi, 2014). Ahuja et al. proposed that BIM connects the concepts of lean construction and green building, built an integrated conceptual framework between lean construction and green building, and confirmed that BIM could promote the implementation of the system through three cases (Ahuja, Sawhney, & Arif, 2014).

Xu et al. proposed the basic model of integrating the key technologies of lean construction with BIM and carried out specific analysis. The main advantages of the integration were described from the aspects of project, business, and industry (Xu, Su, & Wang, 2012). He et al. studied the current situation of lean construction

application from the aspects of Last Planner (LP) and Integrated Project Delivery (IPD). The main factors that hindered the promotion of lean construction were also analyzed from the three levels of environment, organization, and ideas of mathematics thinking (He, Zhao, & Dong, 2013). Gurevich and Sacks, proposed a new process of QC based on the theoretical basis of lean construction to reduce waste in construction (Gurevich & Sacks, 2014). The authors discussed quality management and introduced the key elements of fine construction QC from the aspects of a rolling QC plan and quality function distribution. Chen and Luo introduced methods to control traditional construction quality and analyzed its drawbacks. In addition, they compared traditional construction to the controls under lean construction and analyzed the economic benefits of using lean thinking to control quality (Chen & Luo, 2010). A number of researchers have enriched the theoretical basis of lean construction and proposed means and methods to support lean construction, making lean construction a theoretical and innovation input to the building industry (Ilozor & Kelly, 2012; Dave et al, 2016). From a review of the studies of the above scholars, it can be seen that the study of the integration of BIM technology and lean construction theory is in the initial stages. Based on the experience of former scholars, combined with the existing problems in quality management of construction projects, this study proposes a QC system based on BIM technology and lean construction theory and conducts a case analysis to examine the system. The research results of this study will have practical significance in that they can contribute to improving the quality of construction project enterprises, reduce project costs, and further improve and enrich the lean QC theory. This research also addressed issues, perceptions, and collaboration opportunities to advance BIM education and implementation in the construction industry, provided interesting initial findings, and raised a few fundamental questions for further exploration.

ESTABLISHMENT OF A KANBIM QUALITY CONTROL SYSTEM IN A CONSTRUCTION PROJECT

Kanban is a QC system in which information is carried along the manufacturing process, usually in the form of a board or card. Through the Kanban information, workers have a clear understanding of the arrangement of daily tasks, including the time, quantity of delivery, and delivery requirements, which can reduce over-production (Gurevich & Sacks, 2014). In construction, three types of Kanbans are used for QC: construction information boards, quality acceptance boards, and rework tracking boards, which are all placed at the work entrance of each construction team. In Kanban QC, the construction of the next procedure can only be continued when the quality of the former procedure is qualified. Kanban makes the construction and acceptance criteria visual and provides a clear control sample for construction workers. The construction progress and the overall construction quality of each construction team can be judged according to the construction Kanban and the QC awareness of construction workers can be improved unknowingly.

Conditions to Establish a Quality Control System

The establishment of a 4D BIM model

A 4D BIM platform can be formed by combining the 3D BIM model of a project with a construction scheme, as shown in [Figure 1](#). The following information is imported into the 4D BIM model to build an efficient QC system.

The QC standards of the different levels

The construction process requirements and standards; the acceptance criteria; the targets of quality management at different stages; and the integrated database with suppliers (information on various materials and machineries)

The distribution of the QC function

Positions included in Kanban QC organization are the project leader, regional manager, construction team manager, person in charge of the construction team, person in charge of the safety construction, engineer, and other supervisors. These people are responsible for the formulations of different quality plans, supervision during the construction process, and acceptance of parts of the project at various stages of QC.

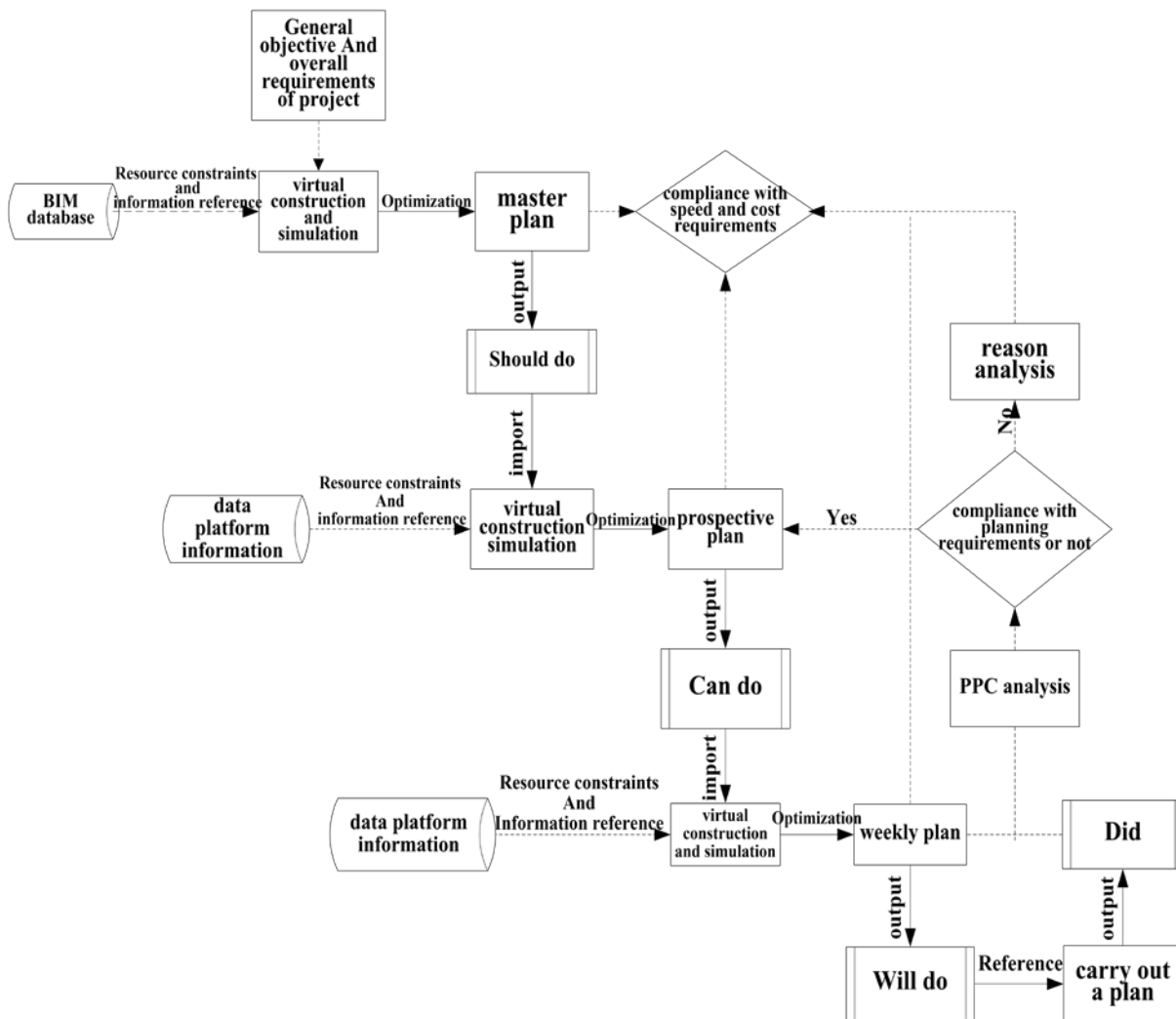


Figure 1. LPS system flow based on BIM database

The establishment of a quality control (QC) team

The QC team is a key team under lean construction. In general, the system that implements KanBIM QC has higher requirements for the quality self-awareness and the ability of the construction workers. The QC team is able to drive team members to adapt to the new QC model and urge them to learn from each other to improve the quality of engineering, which is also the reflection of the continuous improvement principle of lean construction.

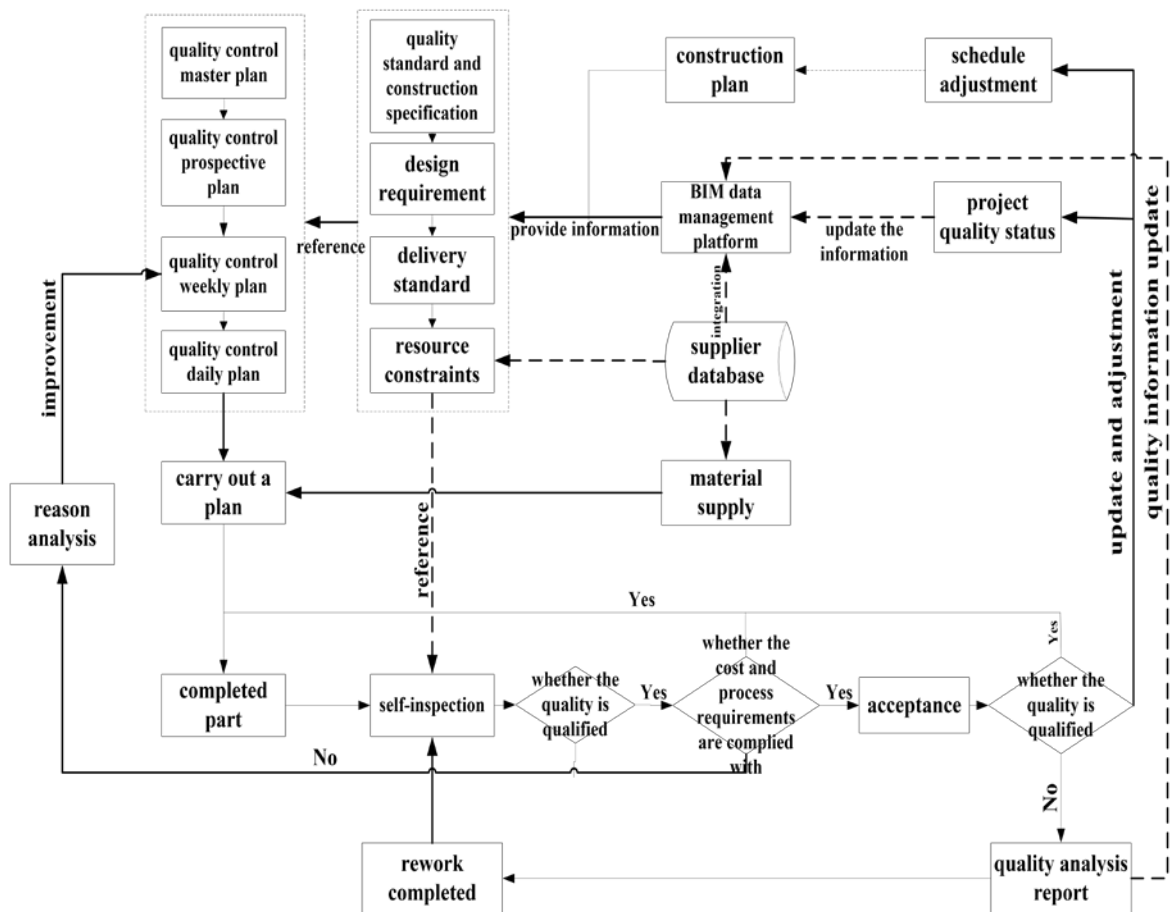


Figure 2. KanBIM QC process

KanBIM QC Process

The framework of the KanBIM construction QC system is shown in Figure 2. The system is built based on the combination of LPS theory and BIM technology, where the visualization of the QC process of each level can be achieved by using virtual construction and simulation technology (Qin, Xia, & Yang, 2014; Deng & Ye, 2015). In addition, the optimal planning can be adjusted at any time using the BIM database information, resources, and the requirements of the progress and costs, thus achieving continuous quality improvement.

The QC plan is part of the project management plan. From the KanBIM QC system, the control process is driven and realized by the master plan, the prospective plan, the weekly plan, and the implementation plan. As a result, the quality of construction can be improved continuously with the establishment of a feedback system of QC information, combined with the dynamic support of the BIM database. The detailed QC flow is shown in Figure 2.

QC master plan

The overall QC plan is formulated according to the design scheme of the project, the overall quality target, the construction program, and the materials supply information. The plan developers are the project manager and the regional manager.

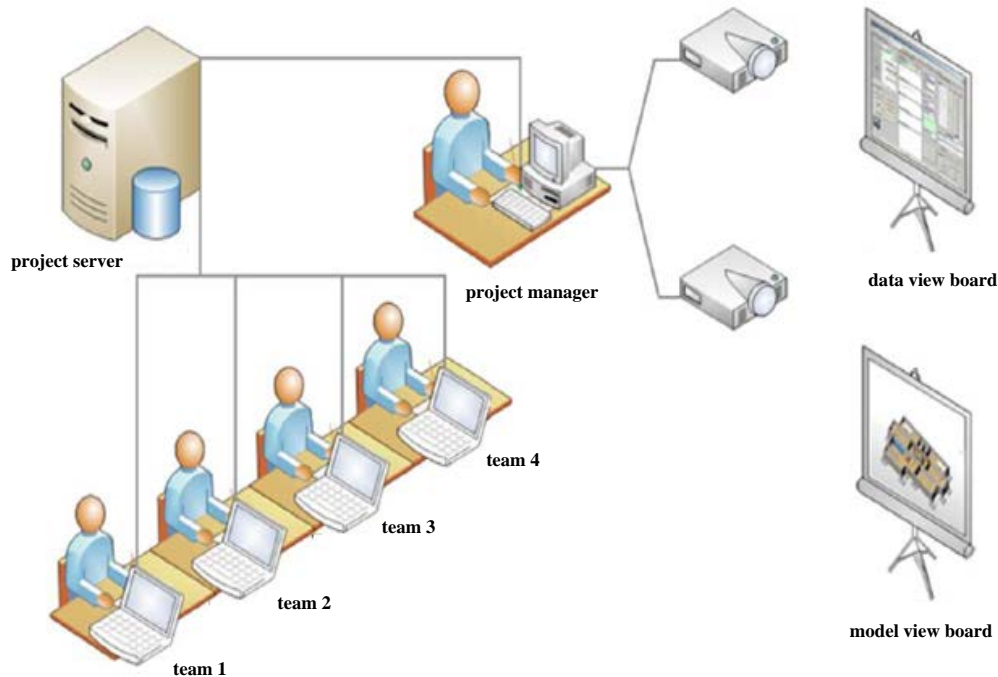


Figure 3. Weekly Plan Meeting

QC prospective plan

The prospective plan is the decomposition of the master plan. Based on the work broken structure (WBS), specific QC plans are developed by considering the decomposed work units as objects and taking into account the material supply and construction constraints between the processes. Here, the upper plan is adjusted and details are explored further, combined with real-time data updates in the BIM information platform.

QC weekly plan

By decomposing the prospective plan of the upper level, the construction team receives the task package and then highlights the tasks with different symbols in the BIM model visual interface to clearly specify the work contents and responsible construction teams. At the same time, the construction teams develop corresponding QC plans in accordance with the quality standard documents and regulatory requirements in the BIM platform and send the plans to the project manager for approval.

The project manager presides over the weekly planning meeting every Monday to analyze and integrate the construction plans and QC plans developed by the different construction teams, thus forming the weekly plan of the entire project. In the meeting, the QC plan has two different display interfaces, namely, the database information display and the corresponding 3D model display, as shown in Figure 3. Database information includes the requirements of the different product parameters in the construction and the limitations of material specifications. The data information of the two is mutually related. The interface is able to switch to the corresponding data information from the four dimensions of the construction team, the construction task, the construction space, and the applicable resources.



Figure 4. Kanban control interface provided for construction workers

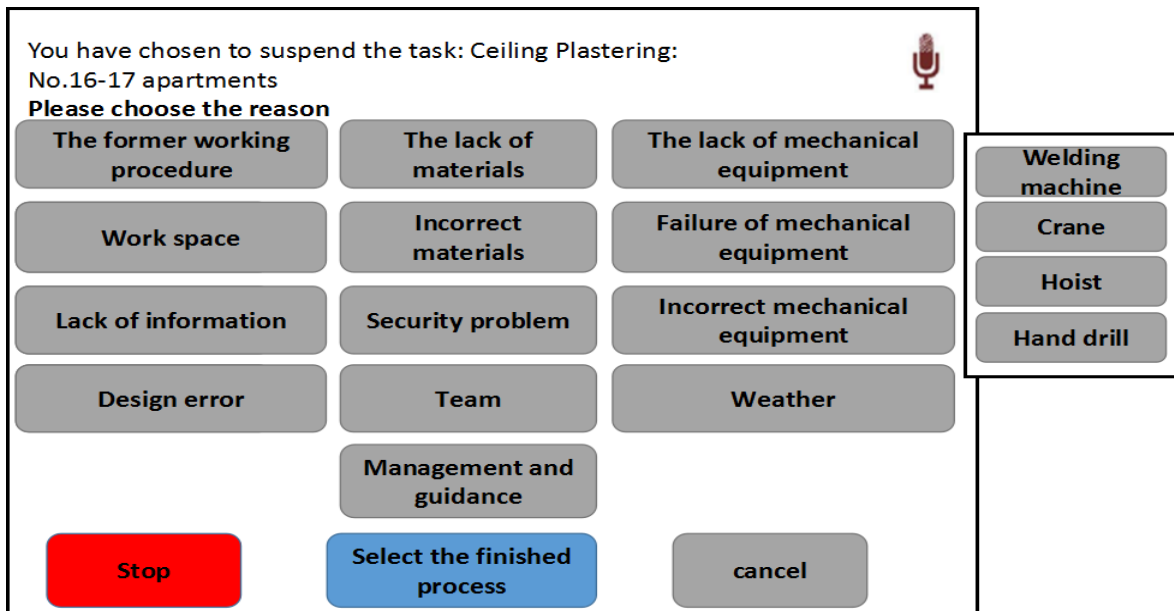


Figure 5. Report interface displays the reasons for construction suspension

Implementation plan of "human-computer interaction"

During the execution process of the weekly plan, the person in charge of the construction team has the right to adjust the daily work according to the actual situation. As shown in Figure 4, the large-screen interface on site displays the content of the QC system, the construction specifications, the disclosed prototype, and the acceptance criteria. By comparing the site completion and prototype in the model, the person in charge of the team conducts self-inspection, finds out the specific quality problems, and then uploads them to the team responsible for solving the problems to improve the weekly plan. With respect to quality problems caused by engineering design, timely feedback and corresponding design improvements are required, as shown in Figure 5.

After the construction is completed, the person in charge of the team presses the button "construction completed" on the big screen, and the inspector receives the acceptance request. If the quality does not pass the acceptance, reword is initiated and the problems will be fed back into the quality of information platform. As a result, the next step in the procedure cannot be continued until the rework acceptance is qualified.

Table 1. Quality status represented by colors

	Quality status	Color representation in model
Before acceptance	Before the construction	Grey
	During the construction	Yellow
	After the construction	Purple
After acceptance	Unqualified	Red
	Qualified	Green

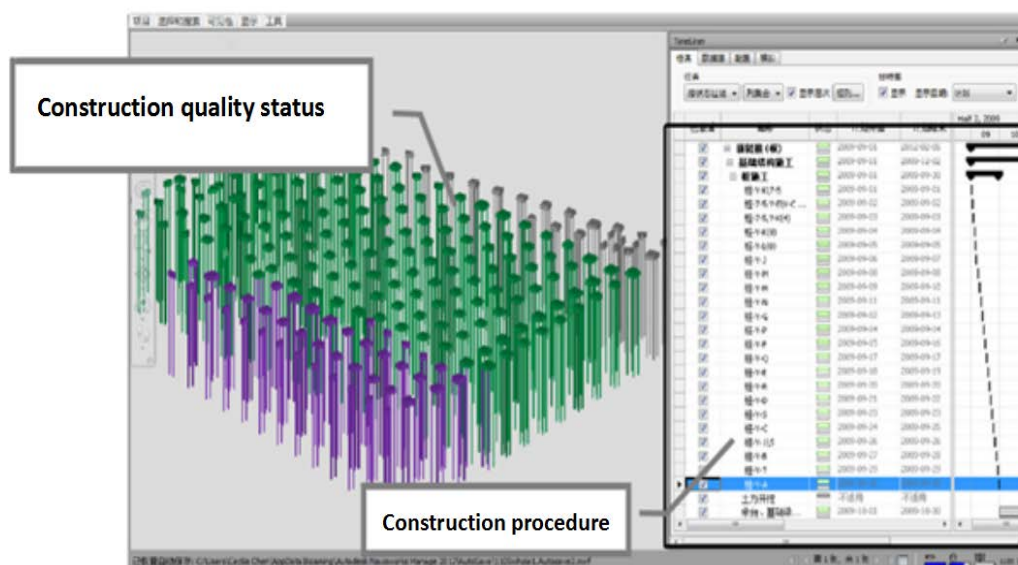


Figure 6. Display of construction quality status – Through color recognition, the user can see that the purple and green represent tasks that are qualified and post construction (completed), respectively

The difficulties encountered in construction and the solutions taken should be reported, whether the plan is completed or not. The purpose of doing this is to collect problems that may arise during the construction and provide a reference for subsequent design and planning.

Update of the quality status

In the QC system, 3D BIM uses different colors to reflect the status of the project, as shown in [Table 1](#), [Figure 6](#).

At any construction phase, the quality status of the entire project is clear at a glance through the color distribution. Any user can determine the progress and quality of the project through this intuitive color distribution. This model is able to provide a clear reference for the development, adjustment, and implementation of plans in the near future.

Organizational Structure under the IPD Mode

In the guidelines issued by the American Institute of Architects in 2007, IPD refers to a project delivery mode in which the personnel, system, business structure, and design plan are integrated. In IPD, the project parties collaborate with each other and integrate knowledge and experience to optimize project results, enhance project value in the design processes, component prefabrication and construction, reduce waste, and maximize

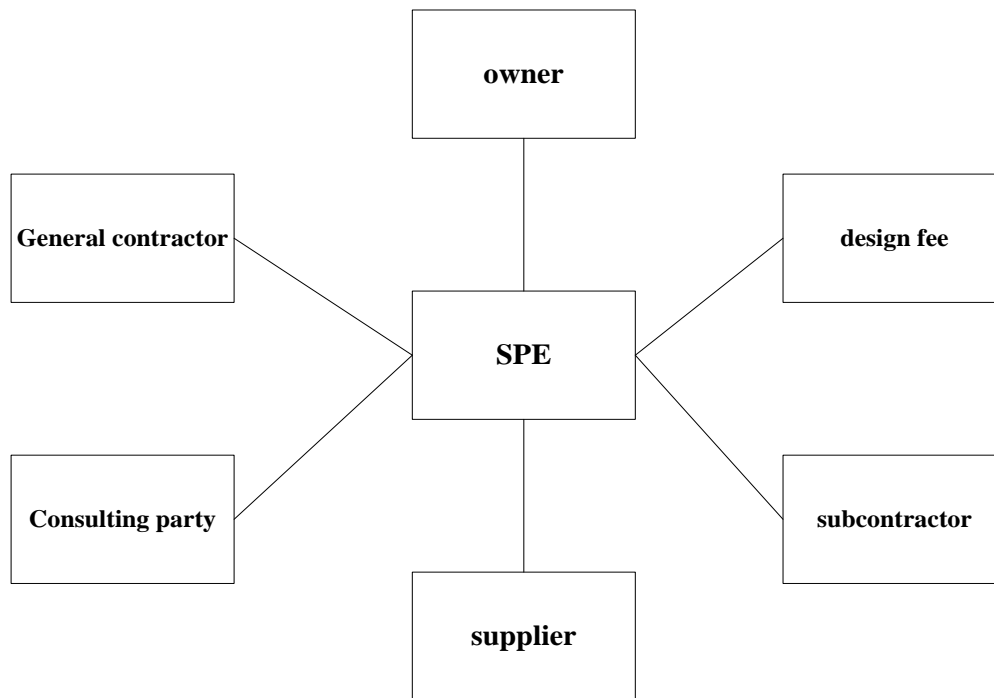


Figure 7. IPD organizational chart under SPE

construction efficiency (TAIO Architects, 2007). Under the IPD mode, the project parties participate in the project from the design phase, collaborate with each other at all stages of the project for overall efficiency, assume project risk, and share interests (Teng, & Wu, 2013). The biggest difference of an IPD project is the contract form. A series of relevant policies and contract standards have been introduced in the United States, Australia, and a few other developed countries where IPD has been widely applied.

At present, the contract form of a single purpose entity (SPE) is widely used in foreign IPD projects (see [Figure 7](#)). SPE refers to the limited liability company (LLC) formed by the owners, project managers, engineers, and other project participants as shareholders (Ma, & Ma, 2017). The owners, designers, and contractors do not sign the contract separately but become an entity, through SPE, to share the project risks and benefits. This form of contract is a new mode of organizational structure brought by IPD, where teamwork can effectively resolve conflicts between the participants and support the overall interests of the project (Jones, 2014).

In this study, the QC system is constructed in the organization structure of SPE. For projects with large volume, high complexity, long construction period, and high operation and maintenance requirements, the adoption of brand new IPD model is quite necessary.

CASE STUDY

The Foshan Municipal Public Culture Complex is located in the core area of Dongping New City, Foshan, which is considered an important cultural infrastructure under construction in China. The total land area of the project is approximately 43,400 square meters, with a total construction area of over 70,000 square meters, including two underground floors and 17 floors above ground. The total height is 153.6 meters. The square tower uses a double anti-lateral force structural system of oblique steel and a steel support core tube, composed of a total of nine cubes, of which four cubes constitute the base while the upper five cubes are not simply superimposed, as in a traditional building, but stagger in different directions and surround the core tube. The key and difficult feature of the square tower construction lies in the steel structure construction. Its biggest feature is the cantilever, and the traditional steel columns are formed into grid-shaped skewers. The four cubes at the upper part are staggered to

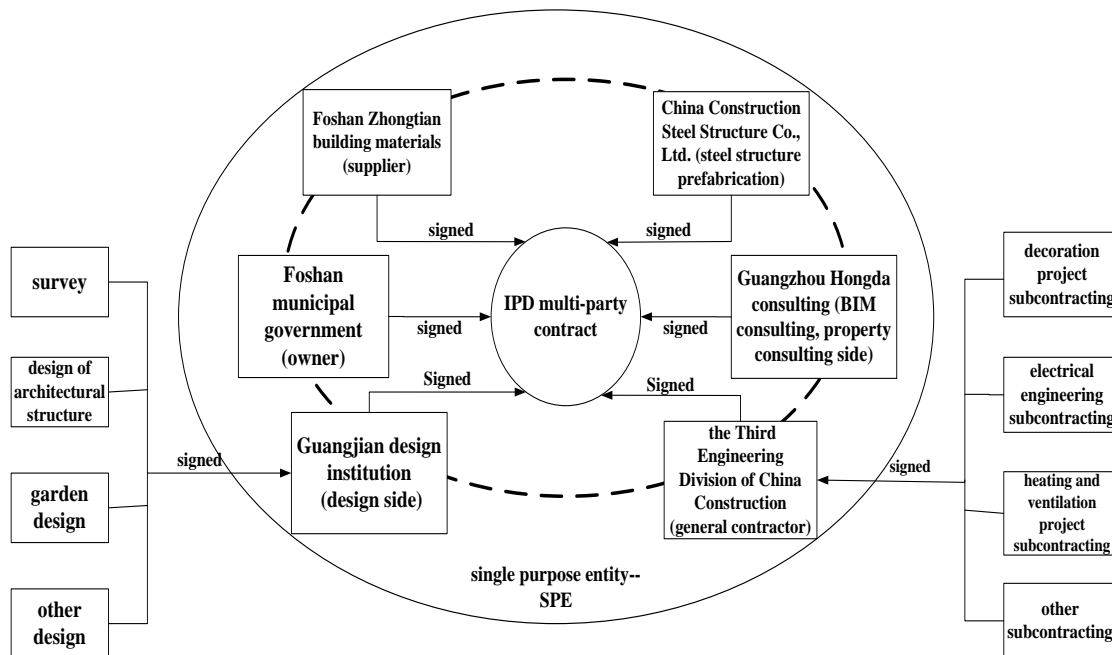


Figure 8. Project organizational structure based on IPD

(Note: Solid arrows indicate contractual relationship, while dotted lines indicate information transfer)

overhang, and the maximum distance of the cantilever is 9.5 meters. The self-weight of the building façade and the indoor load of the cantilever part is borne by the cantilevered structure. Steel works include steel columns, steel supports, conversion trusses, roof trusses, steel oblique columns, and frame steel columns, among other fabrications. The entire project uses more than 10,000 tons of steel. In addition, the pipeline distribution is complex in the underground part; the local pipeline has nearly 30 lines, including wind, water pipes, and a variety of bridges. If a traditional construction and QC method is used for this project, it is almost certain that repeated rework will be needed, resources will be wasted, and the quality of construction cannot be guaranteed.

KanBIM QC Organization Framework under IPD Mode

According to the characteristics of IPD, this study constructs an organizational structure based on an SPE contract that makes better use of KanBIM QC system.

Under the organizational structure of IPD mode, the entities involved in the Foshan Square Tower project, including the municipal government, the design institute, the Third Engineering Division of China Construction, Zhongtian Building Materials, Hongda Consulting, and Steel Structure of China Construction, signed an SPE contract, becoming overall beneficiaries and risk partners of the project. Subsequently, the major parties signed contracts with their respective subcontractors or consulting parties, as required. Such an organization structure enables the construction party, operation, and maintenance unit to get involved in the project in advance; in addition, each participant can obtain the real-time status of the project construction and progress through the BIM platform, thus fully applying the functions of BIM technology. Meanwhile, the project stakeholders can pay more attention to the overall efficiency of the project after becoming an entity through the SPE agreement. All participants are expected to work together and communicate closely, which has a great role in promoting the effective implementation of the KanBIM QC system (see [Figure 8](#)).

Simulated Application Process of the KanBIM QC System

Construction preparation phase

Under the IPD mode, the stakeholders of the project, namely, the entities on the construction side, the design side, the project operation and maintenance personnel, and the future users of the product are all involved in the design and model construction of the project at the initial stages. This can avoid later potential risks and conflicts. Through early studies of the relevant documents and drawings, the construction side is able to improve the design, avoiding possible problems in construction difficulty and construction methods; the operation and maintenance personnel can point out potential problems in the future use of the project; the future users provide product requirements and expectations that reflect the importance of customer needs. The discussions between the various parties and information transmission are realized through the BIM management platform, and real-time information feedback and updates are achieved.

(1) Collision detection

This project has a huge construction difficulty, a complex structure design, and various underground pipelines, so it is necessary to use the visualization function of BIM technology for collision detection. After the completion of the project modeling, collision detection is carried out by comparing the design drawings and models to find all of the potential collision points and improve the design before the construction, thus preventing the occurrence of quality problems. At the same time, the pipeline layout optimization can achieve an orderly arrangement and determine the location of the empty space and the specific size in advance, thus avoiding a complicated pipeline layout or waste of materials and time caused by secondary excavation.

(2) Simulation of the construction process

By applying the virtual design function and construction (VDC), the master plan, prospective plan, weekly plan, and execution plan are carried out with a simulated construction to detect problems and improve the engineering design and the program plan layer by layer, giving the overall QC process more practical value and operability. The ultimate purpose is to “construct the project quality” rather than to control the project quality.

(3) Prefabrication of computer control components

Steel blocks are extensively used in this project due to its unique shape. The computer is used to control the prefabrication of engineering components, and the parameters of specific components in the BIM database are also associated with the information platform of the factory prefabrication department. The corner X-shaped steel components are produced in the factory and the space angle is strictly controlled to guarantee “zero error” of components.

At the construction site, a case-hardened template is used to align and locate the architectural placement of the cubes. The protruding part is aligned at the first layer while the concave part is located at the next layer. To ensure the accuracy of the construction project, the total-station instrument can be used to monitor the key parts and conduct three-dimensional positioning. In this way, the construction quality and accuracy of the project can be better controlled while also expediting the progress of the project.

(4) Integration with the supplier database

It is necessary to integrate the suppliers’ product database while building the Kanban QC system. During the construction process, the construction unit can grasp the material supply and quality situation through the material supply interface, thus ensuring the stability and sustainability of the supply chain. Indeed, the long-term good relations with suppliers resulting from this system are also beneficial for cost reductions.

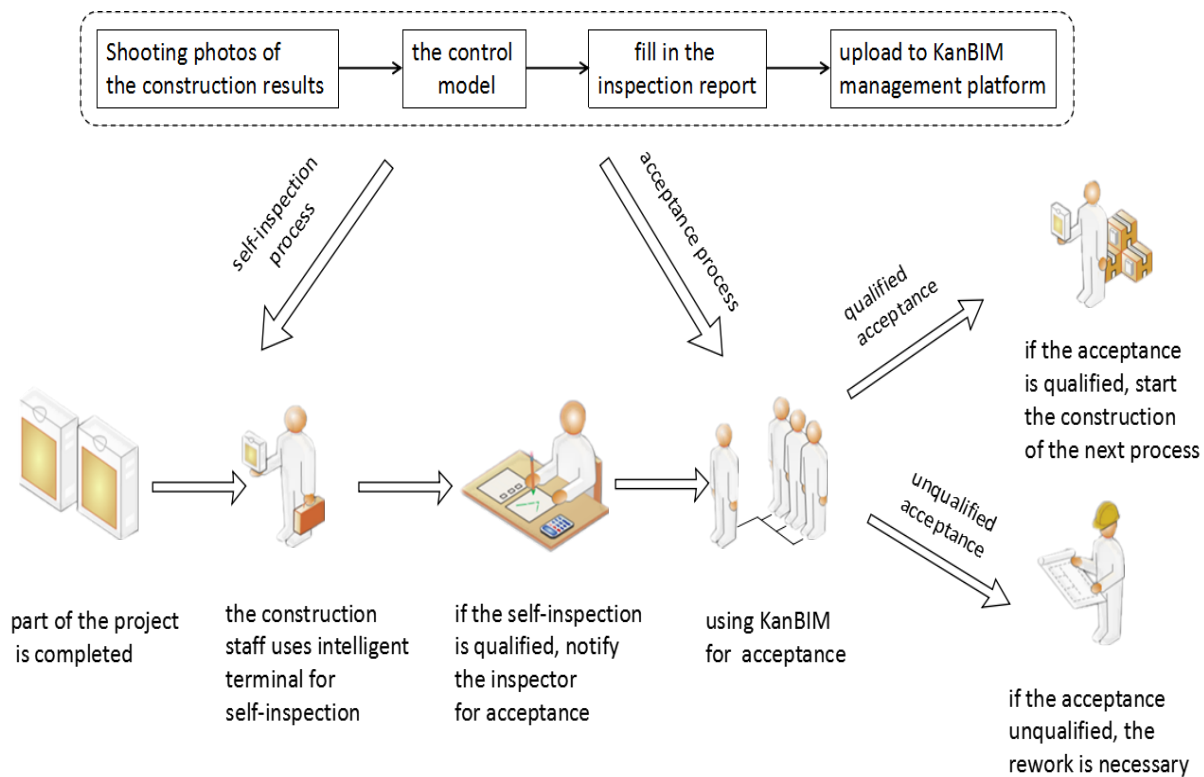


Figure 9. QC in the construction process

Construction phase

In the construction, the project quality is strictly controlled from the implementation of the QC plan, through the construction team self-inspection after the completion of the processes, to the project acceptance and re-acceptance, see Figure 9.

(1) Establishment of the QC team

This project involves the welding of nine square steel structures, so the construction side must establish a QC team before the construction to monitor and implement the QC plan of each layer effectively.

(2) Self-inspection process

After the completion of a portion of the project, the construction team reports the situation through the mobile terminal and then the system automatically generates checkpoints and acceptance content according to the database and model. Thereby, the person in charge of the construction team can finish the self-inspection based on the checkpoints. During the docking process of each block, the docking angle and accuracy among the steel structures are listed in details, including the qualified range and the display of the visualized image. By comparing the construction situation and the display on the electronic screen, the construction can be judged whether it is qualified. Photos of the qualified construction are taken and uploaded to the information platform for the next step of acceptance.

(3) Acceptance process

After the acceptance personnel receive the self-inspection report from the information platform, they take photos and generate acceptance information to fill out a form. The information entered by the inspector will be stored in the database and provide reference for subsequent planning. Next, the system automatically determines

whether the task is qualified according to the form and photos and updates the quality status to the database. In the end, a quality analysis report is generated, indicating existing problems and whether rework is needed.

(4) Rework process

Projects that do not pass the acceptance need to be reworked according to the quality analysis report. The construction team resolves the problem identified in the report and identifies the problematic links and the responsible person to reduce the occurrence of similar problems in the future.

Post-acceptance stage

The QC link after the completion and acceptance mainly aims to improve the enterprise quality management level. The construction side is recommended to establish a group for discussion and learning based on the updated quality problems in the information system. The sources of typical engineering defects, the solutions, and the later effects are considered as primary learning content, which can promote learning in building under lean construction.

Analysis of expected effects

A KanBIM QC system can be used on projects with complex structures, huge construction difficulties, and strict quality requirements. It can conduct real-time supervision and control of quality before, during, and after construction. This level of control helps achieve high standards under lean construction, maximize the value of a project, and control the project's duration and cost in the scope of the plan. A KanBIM QC system is constructed from the perspective of QC, but it also has a positive role in controlling project costs, durations, and safety, among other elements. The impact of the interaction effect between BIM and lean construction is not limited to the management of a certain target; it has a positive impact on the overall optimization of a project and the development of the construction industry. This is the greatest benefit generated by lean construction under BIM technical support.

CONCLUSION

This study constructs a KanBIM construction QC system based on LPS theory. In the system, a KanBIM QC process is initiated and realized through the master plan, the prospective plan, the weekly plan, and the implementation plan. The feedback system of QC information is also established to combine with the dynamic support of the BIM database to continuously improve construction quality. For projects with large volume, high complexity, long construction periods, and high operation and maintenance requirements, adopting the IPD organizational structure under SPE to achieve KanBIM QC system is suggested. In this study, the Foshan Square Tower complex project is presented as a case analysis. The simulation results show that the use of KanBIM QC system on projects with complex construction, great construction difficulty, and strict quality requirements ensures high standards under lean construction and maximizes the value of a project. However, certain obstacles still exist for the full application of the system in the current construction industry, and the difficulties mainly lie in the following aspects: the lack of uniform standards, high technical requirements, high quality requirements for construction workers, and the difficulties of converting from traditional thinking. In addition, an enterprise's organizational structure and construction methods must meet certain requirements before carrying out QC with a BIM system. To maximize the effect of BIM technology and lean construction synergy in project management, the participants of a project need to change their attitudes toward the project body, make efforts to improve the final project value, and exchange information and expertise, as well as improve the awareness of the QC of each link. Moreover, government guidance and encouragement are also needed, particularly in the development of BIM technology standards and related norms.

COMPETING INTERESTS

The authors declare that they have no competing interests.

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