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RESEARCH ARTICLE

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Owner-dominated building information modeling and lean construction in a megaproject

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Abstract The integration of building information modeling (BIM) and lean construction (LC) provides a solution for the management of megaprojects. Previous studies have generally focused on the theoretical or empirical adoption of BIM and LC. Moreover, only a few studies have examined the approach of simultaneously using BIM and LC in megaprojects. Therefore, an intensive study on the application of BIM and LC in megaprojects, particularly to explore considerably effective integrated application modes of BIM and LC in megaprojects, will substantially promote the management efficiency of megaprojects. The current study describes a method that integrates owner-dominated BIM and LC that was developed in a case study. The proposed method provides a framework for all stakeholders to use BIM and LC in a megaproject dominated by the owner. The interactional relations among the owner, BIM, and LC were analyzed and positive interactions were identified. These positive interactions served as a basis for the implementation of this integrated approach in a case study and could be applied to other megaprojects. The megaproject (i.e., airport construction project) was examined to verify the performance of the developed method. Results showed that the integration of BIM and LC dominated by the owner can improve management performance and achieve high quality standard.

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Keywords building information modeling, lean construction, airports, project management

1 Introduction

Megaprojects are large, complex, and typically cost billions of dollars. These projects affect millions of people (Flyvbjerg, 2017), possess a long lifespan, involve complex management, and have considerable uncertainty (Bruzelius et al., 2002; Priemus et al., 2008; Jia et al., 2011). The characteristics of megaprojects pose serious difficulties and challenges to project management (Flyvbjerg et al., 2003; van Donk and Molloy, 2008; Sun and Zhang, 2011). Although many studies on megaprojects have been conducted and many achievements have been attained, numerous problems remain. Hu et al. (2015) investigated the status and trends of megaproject research. They discovered that although many theories have been presented, ideas are generally for site management, cost, time, and risk. Evidently, no investigation has been conducted on the use of information technology and organization and stakeholder management. Shokri et al. (2014) and Ansah et al. (2016) demonstrated that traditional project management methods cannot handle the complexity, specificity, and uncertainty of megaprojects.

New technology and management methods, such as building information modeling (BIM) and lean construction (LC), were utilized in many megaprojects to solve underperformance problems, including time and cost overruns, benefit shortfalls (Han et al., 2009; Flyvbjerg, 2014; Fahri et al., 2015), quality defects, safety accidents, and environmental pollution (Hu et al., 2016). Megaprojects are complex and their impact is considerably broad (Remington and Pollack, 2007). The issues involved in megaprojects are different from those in traditional complex projects. For example, megaprojects are often affected by political objectives of various organizations and local government (Jia et al., 2011). Therefore, the general management methods of complex projects cannot be directly applied to megaprojects without any modification. Previous studies have provided fundamental knowledge on and foundation for the integration of BIM and LC. However, no prior research has conducted an in-depth investigation on the application of BIM and LC in megaprojects, specifically to explore an effective integrated application mode of BIM and LC in megaprojects. Accordingly, a substantially robust approach is required to integrate the usage of BIM and LC in the management of megaprojects.

This study aims to develop a BIM-based LC application method for megaprojects. The remainder of this paper is organized as follows. Section 2 provides a literature review of megaprojects and integration of BIM and LC. Section 3 analyzes the applicability of BIM and LC integration to a megaproject and presents an owner-dominated BIM-based LC application method. Section 4 describes the case study, which is an airport construction project in China, through which the authors demonstrate the application of integrating technology and management using the proposed method. Lastly, Section 5 summarizes the results of the integrated usage of BIM and LC in the case study and discusses the research conclusions and limitations.

2 Literature review

2.1 Difficulties in megaprojects

Megaprojects are projects that are generally considered to cost over 1 billion USD (Shokri et al., 2014; Flyvbjerg, 2017) or from 500 million to 1 billion USD when specific factors, such as scale, complexity, and social impact, are considered (van Marrewijk et al., 2008; Hu et al., 2015). These projects are large scale, require considerable investment in time and money, involve various stakeholders, and have considerable uncertainty (Fahri et al., 2015; Turner, 2016). These characteristics cause significant difficulties in designing and managing megaprojects and could result in underperformance (Haidar and Ellis, 2010; Liu et al., 2014). Flyvbjerg (2014) indicated that the majority of megaprojects cannot achieve the desired objectives and cause time and cost overruns and benefit shortfalls. To effectively manage megaprojects and ensure high management performance, managers should enhance collaborations among numerous partners, manage project complexity, and control project cost and time. The existing literature on megaprojects indicates that the problems encountered in megaprojects can be divided into management and technical problems (see Table 1).

2.2 Applicability of BIM and LC in megaprojects

BIM is frequently used as a tool for coordinating project information with project management in construction projects (Deutsch, 2011; Soh, 2014). Moreover, BIM allows all stakeholders and participants in a project to utilize coordinated, reliable information from the beginning of the project (Azhar, 2011; Soh, 2014). Several studies have introduced BIM to megaprojects to determine if this method can address difficulties in these projects. Liu et al. (2014) developed a BIM-based solution to improve the efficiency and effectiveness of design and construction and applied the solution to a bridge project to demonstrate that a BIM-aided approach can be used in the design and construction of a megaproject. Soh (2014) investigated the characteristics of BIM and revealed that this method can improve quality, shorten construction duration, and improve collaboration among project participants, thereby enabling mega-skyscrapers to be built safely and efficiently. Chong et al. (2016) investigated BIM-related software and BIM-involving activities in different project stages and subsequently analyzed and compared the use of BIM in two infrastructure projects; both projects were successfully completed in terms of cost, time, and quality of construction workmanship by applying BIM. Hu and Chan (2011) established a management organization approach, applied it to the BIM-based Shanghai World Expo Construction megaproject (Chien et al., 2014), and successfully procured this project with high performance. These studies have concluded that the BIM features can address the difficulties in megaprojects from the theoretical and practical perspectives and that BIM is a valid technology that facilitates the achievement of the required outcomes of megaprojects.

Table 1 Difficulties in megaprojects

Category	Main problems	Description
Management	Organization management	Numerous project participants, complexity in administrating levels, vertical connection is cumbersome and lacks horizontal connection
	Information management	Many engineering data sources, complex communication between participants, information transmission distortion
	Coordination management	Heavy workload in coordinating division of labor, resource allocation, and project objectives among functional departments
Technology	Difficulty in construction	Numerous applications of new structures, materials, and technics
	Complex building structure	Architectural modeling and spatial relations are complex, while structural forms are complex and diverse
	Schedule control	Short construction period, substantial crossover work, and numerous engineering changes

LC is a management method that relies on production management principles and its goal is to meet customer needs while using minimal resources (Sacks et al., 2009). The essential features of LC include clear objectives, waste elimination, satisfaction of customer needs while ensuring maximum performance (Sacks et al., 2010a) and control throughout the entire lifecycle (Best and de Valence, 2002; Rahman et al., 2012). Project complexity is a reason for poor performance, time delays, and cost overruns. Ansah et al. (2016) and Sohi et al. (2016) examined LC and its principles and revealed that this method is a robust means of project management, can help address project complexity via lean principles, and can enhance performance. LC is also a solution to the variability and uncertainty existing in the execution of project plans (Best and de Valence, 2002; Salem et al., 2006) and substantially improves productivity in production process control (Salem et al., 2006; Senaratne and Wijesiri, 2008). In summary, LC is applicable to megaprojects because of this method's features that correspond to the complexity and underperformance of such projects.

2.3 Integration of BIM and LC

BIM is a transformative information technology and collaborative visualization tool, while LC is an advanced approach for the management of construction projects. Through a literature review, the authors conclude that BIM and LC are appropriate for solving the difficulties in megaprojects. However, instead of applying BIM and LC independently, integrating the BIM features with lean principles would bring substantial benefits to the management of megaprojects. The question is whether the two approaches can work together in megaprojects or whether BIM and LC can be integrated for use in projects.

BIM is a tool that can play an important role in the entire project lifecycle (Saldanha, 2017). The focus of BIM is to increase productivity and quality and eliminate all or the majority of the drawbacks of traditional methods (Omoregie and Turnbull, 2016). LC begins from the initial stage of a project to the handover of a facility to the client (Best and de Valence, 2002). The focus of LC is often to reduce waste, increase customer value, and seek continuous improvement (Sacks et al., 2009; Koskela et al., 2010). When applied in projects, the two approaches have a similar goal (Villa et al., 2017) of adding value and eliminating waste. Thus, synergy exists between the two methods (Rischmoller et al., 2006).

Li et al. (2017b) compared the LC levels of two firms and discovered that one of the factors that hinder the adoption of lean concepts is low-level informatization that causes frequent delay in project delivery. Dave et al. (2016) indicated that BIM could address LC management in a visual manner and proposed an enhanced LC management system to generate a smooth information flow, thereby ensuring efficient production management and control. The Lean Construction Institute reported that approximately 57% of productive time waste could be found in the construction industry (Ansah et al., 2016). Doloi et al. (2012) and Mahalingam et al. (2015) believed that many projects were plagued by cost and time overruns because of poor information sharing and lack of coordination among the participants. Mahalingam et al. (2015) conducted a case study on BIM and LC usage in two Indian projects and concluded that BIM is a digital platform through which project teams could share information effectively; when coupled with LC, BIM can effectively improve project performance. Therefore, BIM is expected to provide a foundation for the results that LC is expected to deliver (Sacks et al., 2010a).

In general, BIM-enabled projects are tightly coupled technologically but divided organizationally (Dossick and Neff, 2010). Won et al. (2013) believed that many factors restricted the effective adoption of BIM and argued that organizational readiness is crucial in applying BIM to projects. Moreover, many studies have presented the importance of aligning BIM with project processes (Mahalingam et al., 2015). Given that BIM is regarded as a collaborative tool in projects, several studies have used LC to address the issue of improving coordination among project participants on the basis of BIM. LC approaches, such as last planner system (LPS), visible management (VM), conference management (CM), just-in-time technology (JIT), concurrent engineering (CE), total quality management (TQM), and 6S on-site management (6S), have also been applied to project processes (Koskela et al., 2002; Li et al., 2017b). Won et al. (2013) performed a case analysis and confirmed that LPS contributes to BIM adoption, thereby indicating that lean practices enable BIM adoption. Bi and Jia (2016) reported that the key LC approaches can be integrated with BIM. They conducted a case study on Shanghai Tower to evaluate the quantitative effect of the integration method and showed an increased efficiency in managing the project.

From these research and case studies, the current authors believe that BIM and LC can be integrated for use in megaprojects. BIM and LC substantially complement each other in the technological and management aspects. However, experience on the integrated usage of BIM and LC in megaprojects is lacking. The current study demonstrates the application of a method that integrates an owner-dominated BIM and LC. This method is elaborated and discussed in the subsequent sections, in which a Chinese airport megaproject is used to confirm the validity of the proposed method.

3 Owner-dominated BIM-based LC application method

3.1 Research method

This study adopts the literature analysis and case study methods. First, the features of megaprojects and the difficulties caused by these features are analyzed on the basis of the literature review, while the effects of BIM and LC in solving the problems of megaprojects are investigated. Second, the purpose and benefits of the BIM and LC integrated application in megaprojects are explained through the analysis of the complementary roles of the two methods. In the following sections, by analyzing the benefits of owner-dominated and interactions among owners, BIM and LC, the feasibility of integrated application of BIM and LC under owner-dominated is verified. Based on this, an owner-dominated BIM based LC application method is proposed. Lastly, this method is applied to an airport megaproject case, while the effectiveness of the proposed method is tested by analyzing the application results.

3.2 Why owner dominance

The value of a project represents the interests of the owner. Hence, the more value added to the project, the more benefits the owner receives. LC is a value-optimizing management tool for owners, architects, designers, engineers, constructors, suppliers, and end users. This tool aims to eliminate all non-value-adding processes in the system (Ashworth, 2013), while any participant who uses LC aims to add value to projects while avoiding additional costs. However, when BIM is used in projects, any participant (including the owner) could use BIM for their own purpose, although such a purpose can be different. The primary purpose of an individual participant could be to serve himself by increasing efficiency or quality of work or maybe even learning. However, adding value to the project is only a secondary purpose. Although this objective is good, the goal is not necessarily for the general efficiency of the entire project. When the owner starts to use or enforce the use, its purpose must be for the entire project to maximize the overall gains. In the current study, the term “owner-dominated” refers to the owner who enforces and supervises all participants to use BIM and bears the costs of BIM usage.

Previous studies have confirmed that the owner-dominated method is conducive to the BIM application effort. Li et al. (2010) utilized real-life examples and compared and analyzed the current approaches of BIM and found that the most efficient approach among all current approaches is the owner-dominated BIM application approach. This superiority is primarily due to the fact that in the owner-dominated BIM application approach, the owner can participate in all stages of a construction project, while BIM is a technical means that can be applied in the entire lifecycle (Cerovsek, 2011). Song et al. (2017) also found that top management support exerts a positive influence on BIM user satisfaction, which is one of the indicators to assess the overall BIM performance (Shin et al., 2015). The owners are the major managers of projects and the largest beneficiary that should bear the greatest responsibility to promote BIM (Li et al., 2017a). Moreover, strong insistence from owners can help counter and overcome resistance to BIM (Holmström et al., 2015).

From the existing research, we can conclude that the greater the application depth and breadth of BIM and LC in a project, the better the benefit of such a project. Meanwhile, the owner represents the overall benefit of the project. Therefore, we speculate that only under the owner’s leadership, the greater the driving force of BIM and LC will be, the greater the application depth and breadth will be, the greater the benefits of the project value-added.

3.3 Interactions among owners, BIM and LC

The owner-dominated BIM and LC integrated application mode has three core elements, namely, owner, BIM, and LC. The features of these elements have been analyzed from the perspective of practicability. Moreover, the three elements can be aligned because they have the same purpose of improving the project value.

The most evident advantage of BIM is information management, whereas that of LC is management optimization. Owner dominance can increase the flexibility of applying BIM and LC. The current study draws the following conclusions: 1) BIM and LC can be integrated in construction projects; 2) BIM and LC are advanced tools for project participants; 3) Owner-dominated mode is the best means to enhance the value of BIM. Therefore, positive interactions exist among the core elements. Accordingly, these interactions are the foundation of this application mode. If the core elements are used in the entire lifecycle, then the undesirable phenomenon of being separate and non-continuous in different project phases (i.e., the preparation, design, construction, and operation phases are often independently executed) can be addressed.

3.4 Integration framework of BIM and LC

The current authors used the functions of BIM and LC as bases to develop an owner-dominated BIM and LC integrated management mode that can be used in megaprojects. Figure 1 shows the integrated framework of BIM and LC. This management method actualizes an entire lifecycle application framework, the ultimate aim of which is to meet customer needs. The essential premises for using this framework are as follows: 1) supervised by the owner, 2) all project participants are involved, 3) the framework is used in the entire lifecycle under the condition that the three elements can be continually and positively promoted.

The work procedure of this framework is as follows. The owner supervises the entire lifecycle, while all participants use BIM as the collaborative environment through which a

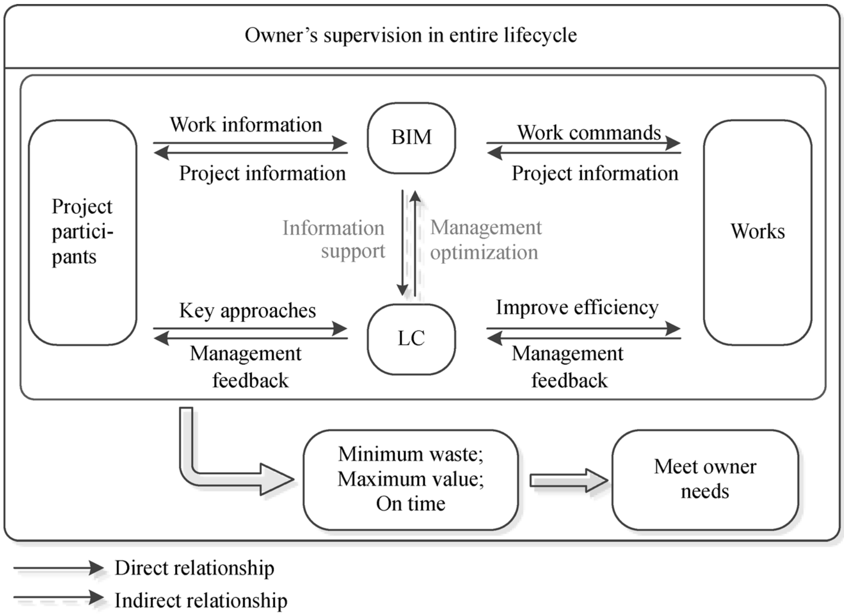

Fig. 1 Integrated framework of BIM and LC.

project participant can issue commands directly to other participants. Moreover, every participant can obtain accurate project information. The project participants can use BIM as basis to utilize the LC key approaches to improve work efficiency. Management optimization is often required to foster close collaboration among the different participants. When participants deal with project work, BIM and LC affect each other indirectly and are beneficial to completing the work with minimum waste, maximum value, and no delay. The expected result of this framework is that all participants reach the goal of meeting customer needs.

After establishing the integrated framework of BIM and LC, the authors investigated how the framework acts on projects and if it can be used to successfully meet customer needs. Therefore, the proposed application mode was used in a Chinese airport project to examine its validity.

4 Case study

The selected project is Zhengzhou International Airport Phase II Project (ZZAII Project), in which the current authors participated as consultants. Thus, the authors were given access to all project information. Data were collected from December 2013 to February 2016, while the BIM models were primarily built in the design and construction stages. The related documents and on-site management information were gathered in the construction stage, while the performance-related information was obtained at the end of the project. Validity and reliability were reviewed and verified by the managers in charge of each company to ensure that these processes uphold the validity and reliability of case study approach (Chong et al., 2016).

4.1 Background

ZZAII Project is a typical megaproject, in which the gross building area is 960000 m^2, while the total investment is 19.1 billion yuan (approximately $ 2.97 billion). This airport is designed to be achieved by air modes, highways, subways, high-speed rails, and other traffic modes. The major projects include the flight, terminal, freight, and facility zones. Table 2 shows this project's major difficulties and their causes. The traditional management mode that focuses on time, cost, and scope is inadequate in

Table 2 Difficulties and their causes in the ZZAII Project

Difficulties in	Causes
Collaboration management	Numerous project participants, over 150 bid sections (sub-projects)
Information exchange	Many engineering data sources
Schedule control	Incomplete information exchange
Complexity	Large-scale building structure and MEP engineering are complex
Quality control	Requirements for high precision in construction and complex techniques in the grid structural steelwork and GTC ceiling
Data quality	Owner claims an intelligent managing platform based on building information models at the end of the project

collaboration management because of the difficulties and challenges encountered by the megaproject (Weaver, 2010). To meet the needs of owners, managers should solve the technical bottlenecks during the entire lifecycle of the project and use a new managerial approach to enhance the management performance of the project. Hence, BIM and LC, which are two state-of-the-art methods that can solve technical and managerial issues, can be applied together in this project.

The best way for BIM and LC to be accepted in a project is when the owner imposes these methods in the contract, even though the owner does not play a vital role in its implementation (Porwal and Hewage, 2013). For the ZZAII Project, BIM and LC were imposed in the contract. The owner was involved in project management and supervision, while a BIM consultant (the author's organization) was hired to reduce the pressure on the owner to apply the integration of BIM and LC. To maximize BIM and LC, the owner and consultant agreed that the owner-dominated BIM and LC integrated application mode can be used in this project. The owner assumed responsibility for the supervision of the BIM and LC application, whereas the professional BIM consultant assisted in the management process to mitigate the skill deficiencies in using BIM. The main duties of the third-party consultant are as follows: 1) guide project participants regarding BIM implementation, 2) generate implementation strategies and activities, 3) perform the process of project lifecycle management (Barison and Santos, 2010).

4.2 Organization structure

Traditional project management cannot address the complexity, specificity, and uncertainty of mega construction projects (Sun and Zhang, 2011). Although the project management integrated BIM and LC in the ZZAII Project, the managers were confronted with the same challenges as those in traditional project management. An organization is an element of project complexity and involves project staff and various teams (Maylor et al., 2008; Lu et al., 2015). A proper organization structure is conducive for enhancing the effectiveness of project staff members and various teams in the execution of a project. Figure 2 shows the organization structure of the ZZAII Project.

The major participants in this project are the owner, designer, consultant, construction firms (i.e., civil and structural steelwork contractors), and material and equipment providers. To better use the management mode in this project, the owner and consultant of the ZZAII Project set up a special BIM-based LC management group to achieve the close integration of the BIM and management organization. The BIM-based LC management group consists of the coordination, schedule, and design management groups. Each management group consists of members from the different participants according to their competence.

The coordination management group consists of the owner and consultant and its main duties are to help achieve coordinated work among the participants, maintain the BIM platform daily, and manage and collect data and

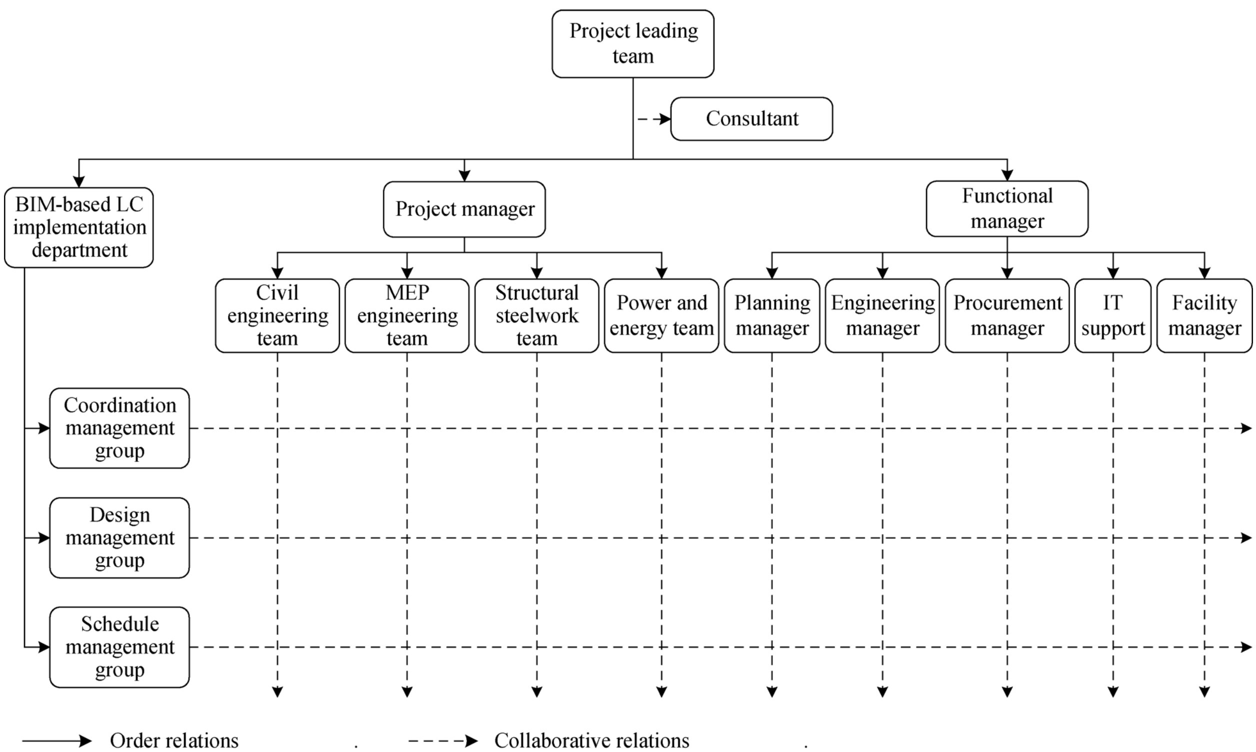

Fig. 2 Organization structure of the ZZAII Project.

document files. The design management group consists of the owner, consultant, and designer and its main duties are the distribution and collection of design drawings and 3D models, design review and changes, and as-built model collection. The schedule management group consists of the owner, consultant, and construction firms and its main duties are the effective control of the construction process, comparison of planned and real-life schedules, and coordination of key construction processes. In each management group, the members of different units can participate in the management work together. This form of management benefits information exchange and communication among the participants and is highly conducive to collaboration work.

4.3 BIM unified standard

Megaprojects are consistently composed of many individual project groups, while the objective of each group differs from that of the others. Thus, conflicts in resources and schedules among individual project groups are the main features in managing megaprojects. Standardization is an LC principle that can provide managerial solution to these conflicts (Sacks et al., 2010b). The ZZAII Project is a BIM-aided project. Therefore, the establishment of project standardization is mainly based on BIM. The BIM unified standard is a unified regulation for participants dealing with project information. This standard is between the organization and information layers and limits how participants centralize and utilize the project information.

In the preparation stage of this project, the owner compiles the project strategies and BIM implementation plans to clarify the responsibilities and workflow. Accordingly, the consultant applies the BIM unified standard to each participant's business to work with LC. The BIM unified standard contains the technical, working, modeling, special application, and delivery standards of virtual models. This standard also involves building, sharing, and using building information models in the project lifecycle, data format requirements, data exchange principles, and other project-related requirements.

4.4 BIM-based workflow

Traditional construction management focuses on conversion activities but disregards flow and value considerations (Senaratne and Wijesiri, 2008). LC can be applied to reduce workflow waste because conventional methods are inadequate to eliminate such a waste (Ansah et al., 2016). From this viewpoint, workflow design can help management groups work cooperatively while adhering to the unified standard. Lean management requires a BIM technology platform, while the platform provided by BIM technology should realize the functions of information centralization, information inputting, and information utilization. A BIM-based collaborative workflow that conforms to lean thinking should be established to facilitate functional realization and enhance the synergies of the project. Figure 3 shows the BIM-based workflow of the ZZAII Project.

4.5 Solution to technical difficulties

BIM helps solve technical problems and provide information support to LC. Figure 4 shows the general workflow to solve the construction difficulties. 1) The problem holders (often construction firms) propose technical difficulties. 2) The coordination management group helps problem holders obtain the related information. 3) The problem holders build 3D models and 4) use the CM approach of LC to obtain a solution once the models are established. 5) The problem holders analyze the information in a visual manner and simulate the solution by using a computer to confirm its feasibility. 6) Lastly, if the solution is feasible, then the problem holders offer the relevant information to the schedule management group to develop a construction plan.

Given the BIM- and LC-aided general workflow, technical difficulties, such as site layout, schedule control, GTC (Ground Traffic Center) ceiling, GTC grid structural steelwork, and MEP (Mechanical, Electrical, and Plumbing) engineering, can be solved effectively. The installation of the GTC grid structural steelwork is the most complex among the engineering difficulties, particularly given its gross area of 53500 m^2 and total weight is of 3000 t. The GTC steel BIM team consists of five individuals who are mainly responsible for detailed design, modeling, and construction technical management. In the detailed design stage, the materials and other requirements for construction are procured using Tekla software according to the original design schematics. The component details and material lists are generated using Tekla software, while the information is provided to the material provider for mass production.

Hoisting of the structural steelwork faces large-body and high-precision challenges. To address these issues, the coordination management group and BIM team collect the relevant data and documents from each participant (e.g., civil work models, relevant labor information, working parameters of mechanical equipment, and on-site information). The GTC steel BIM team establishes a 3D information model on the basis of the general workflow. Thereafter, the relevant participants visually propose the hoisting solution together by using the CM approach. According to the solution, the BIM team simulates the hoisting process. If the solution is feasible, then the construction unit compiles the working and resource allocation plans. These plans are eventually provided to the schedule management group.

In the hoisting stage, the schedule management group is responsible for resource deployment and schedule control. The on-site camera and surveillance system is used to

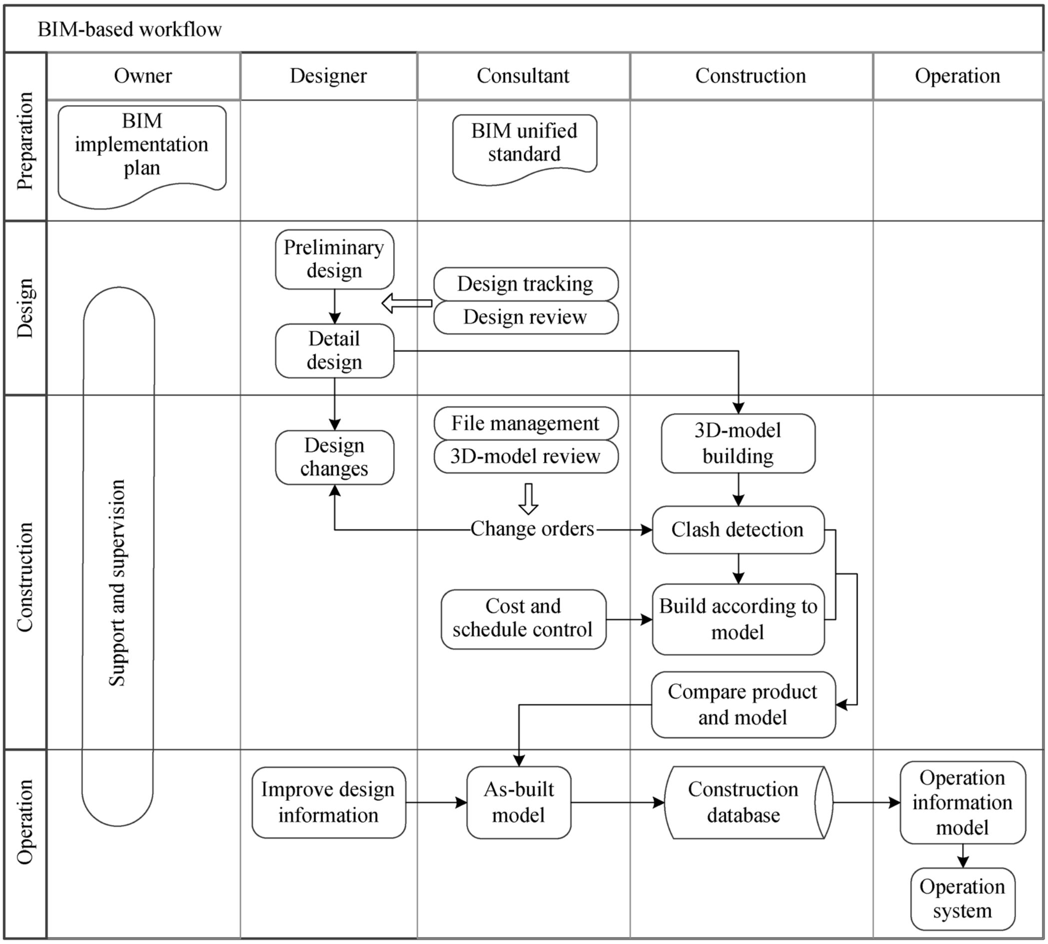

Fig. 3 BIM-based workflow.

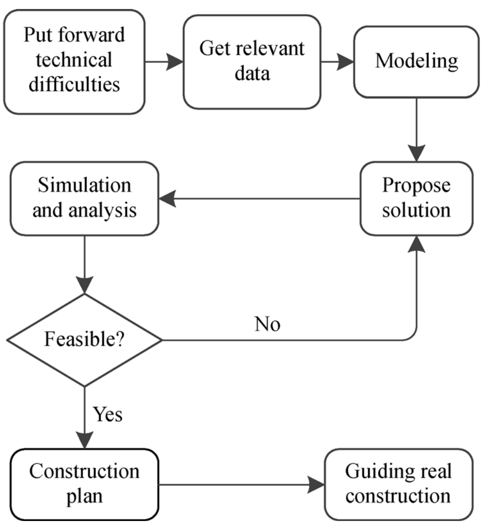

Fig. 4 Workflow for solving technical issues.

grasp the process of the project in real time. Moreover, a dynamic adjustment of resource deployment can be completed in comparison with the process in the working plan.

5 Application results

The project, which began on March 1, 2013, was expected for completion on December 31, 2015, but eventually ended on December 22, 2015. The planned investment was 15.65 billion yuan, the final cost was 19.1 billion yuan, and the cost overrun rate was 22.04%. All participants in this project used BIM and LC in accordance with contract requirements, thereby achieving the project objectives earlier than scheduled and in the most cost-saving manner. By examining the project achievements and interviewing the managers and foremen, the current authors found that the presented application mode was the major cause of this success because it encouraged coordinative capability and enforced the execution of BIM and LC among the different participants. Thus, time and cost consumption were effectively eliminated. The ZZAPII Project was completed nine days earlier than the planned schedule. Although cost overrun was noted, the corresponding rate was acceptable. With regard to the discussion of the project results, the present authors focused on the gains derived from the presented management method. The main reasons for the gains are concluded as follows.

1) The errors and omissions in design and construction work were reduced, thereby eliminating delay and cost wastage and enhancing the continuity of the design and construction phases. The effects of applying BIM included reduced design changes, conflicts, and material losses. Meanwhile, the major objective of applying LC was to help BIM achieve its desired results in the project processes. Design and construction are important phases of construction projects and they are separated in the conventional management mode. Therefore, many design errors are revealed during the construction phase, while several others are revealed even after execution. Hence, construction can only be continued after the design errors are corrected, but the work that has been done in accordance with the design errors can only be rebuilt after demolition, which is time and cost consuming. In the ZZAPII Project, unified standards and BIM-based workflow were formulated, in which all participants could work collaboratively. Before each work began, the constructor's BIM team reviewed the design work by virtual construction simulation. Once design errors or omissions were identified, change orders were delivered to the designer via the design management group. Thereafter, the designer handed over the modified design data to the constructor. Compared with traditional design review, BIM-based work improved accuracy and work efficiency and effectively reduced the cost and delay caused by design errors and omissions. The data on user usage provided by each construction unit indicate that the total cost savings of 34.55 million yuan due to waste reduction during the construction phase were calculated. Table 3 shows the calculation results and principles.

2) The time required was reduced by improving the technique application and coordination in the construction phase. The construction work required high construction accuracy. Thus, the BIM construction teams often used the Revit software for design development and exported the parameters of the various components for mass production. The construction work also required complex techniques. Therefore, the participants could efficiently seek the most reasonable construction plans in accordance with the workflow of solving technical difficulties and reduce inefficient meetings and project duration by optimizing the construction sequence. In the concrete construction process, all participants followed the integrated framework to complete the work. On the basis of BIM and by using the LC key approaches to make the construction process efficient. The equipment, materials, and labor needed were planned before construction. In addition, the time and sequence of access and exit of equipment, materials, and labor were identified on the basis of virtual construction. During the construction process, the owner participated in construction management via the coordination and schedule management groups. The coordination management group was responsible for coordinating the work of all participants to ensure that the materials, equipment, and labor are arranged as planned. The schedule management group was responsible for the overall progress control to avoid construction delay.

3) The technical bottlenecks and management problems have been effectively improved, while the overall project performance has been enhanced. The application effect of BIM is embodied in reducing engineering change and enhancing project management informatization, as well as provides information support for LC in project application. The application effect of LC is reflected in the progress and cost saving of the project and can promote the application of BIM in the project through management optimization. In the ZZAPII Project, technical problems (e.g., site layout, schedule control, GTC ceiling, GTC grid structure steelwork, and MEP engineering) are effectively solved with the help of BIM- and LC-aided general workflow, while management problems (e.g., collaboration management and information management and exchange) are effectively improved.

4) The owner's dominance ensured the participants' usage of BIM and LC in the entire lifecycle. The owner enforced the application of BIM and LC among the project participants, while the BIM consultant offered technical support to enable the implementation of the results. BIM and LC can be used by any participant in the construction projects. The application of BIM and LC by the participants in the entire lifecycle is one of the requirements for maximally adding value to the project. In the ZZAPII Project, the owner was the driving force bearing the greatest responsibility for promoting BIM and LC. By contrast, the BIM consultant assisted in the project process. In this manner, all participants could smoothly apply BIM and LC in the project's entire lifecycle. The interview with the managers among the main participants showed that the promotion of the owner encouraged the participants to apply the two new technologies. Accordingly, the barriers to the application of BIM and LC in this project were reduced, thereby subsequently promoting the implementation of BIM and LC in this project.

Table 3 Reduction of waste in the construction stage

Engineering Classification	Calculation Principle	Calculation Results
Civil Engineering	Reduce 1 serious collisions × 0.005 million yuan	6266 × 0.005 million yuan = 31.33 million yuan
Steel Structure Engineering	Reduce 1% material loss rate × 0.7 million yuan + save 100 man-days × 0.02 million yuan	0.7 million yuan + 2 × 0.02 million yuan = 0.74 million yuan
GTC Ceiling Engineering	Reduce 1% material loss rate × 1.2 million yuan + save 100 man-days × 0.02 million yuan	2 × 1.2 million yuan + 4 × 0.02 million yuan = 2.48 million yuan

6 Conclusions

Given the current economic development, numerous megaprojects are expected to be developed in the future. An effective management mode that integrates BIM and LC is required to counter the problem of underperformance of construction projects. Many studies on BIM and LC have been conducted to resolve this problem in construction projects. Our literature review indicated as follows: 1) BIM and LC can be used in the entire lifecycle of a construction project (Best and de Valence, 2002; Azhar, 2011; Cerovsek, 2011; Rahman et al., 2012). 2) The owner-dominated BIM application mode is the most beneficial to the BIM value (Li et al., 2010; Holmström et al., 2015). 3) The application of LC can add value to a project (Sacks et al., 2009; Koskela et al., 2010). 4) Lastly, BIM and LC have a positive interaction and can be integrated in construction projects (Rischmoller et al., 2006; Sacks et al., 2010a; Won et al., 2013). However, these studies have generally focused on the implementation methods of BIM and LC. Only a few studies have examined how to integrate BIM and LC to further enhance THE management of megaprojects.

On the basis of these reviewed studies, the current authors believe that the owner-dominated mode is conducive for the further integrated application of BIM and LC. Through a case study, the authors presented an application mode that integrates BIM and LC, analyzed the applicability of this application mode in megaprojects, and verified its practicality. The results of the case project indicated that this application mode of BIM and LC plays a significant role in collaborative management and information integration and facilitates the improvement of project performance. The following conclusions were obtained:

1) The owner-dominated BIM-based LC management mode can empower the owner as a leading figure in project management by requiring stakeholders to use BIM and LC in the project process.

2) This management mode can improve coordinative management capability, which can effectively eliminate the separation between the design and construction stages.

3) This application mode of BIM and LC allows technology and management to be substantially integrated.

4) This management mode can cope with the underperformance issues (e.g., time and cost overruns, benefit shortfalls, and waste) of megaprojects.

The proposed owner-dominated BIM-based LC application mode can provide an effective framework for project participants in using BIM and LC. Evidently, the findings of this study are suitable for projects, in which the owner is involved in the entire lifecycle management. Although the object of this case study is an airport construction project, megaprojects have many features in common, such as large investment, numerous participants, complex information, and various risk factors. Thus, other mega or complex projects can refer to the management mode presented in this study as a basis to improve innovation.

However, no one-size-fits-all method/solution is available to solve all the problems of construction projects. From the perspective of applicability, the premise of the proposed method is that the owner is primarily responsible for BIM and LC in the entire project lifecycle. Furthermore, each project phase has its own characteristics. Hence, this study merely presented an application framework and verified its applicability. Accordingly, the detailed application of BIM and LC to every project stage requires further research.

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