Using BIM to Improve the Design and Construction of Bridge Projects: A Case Study of a Long-span Steel-box Arch Bridge Project

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Abstract More and more mega-complex bridge projects are being or will be built worldwide. At the same time, the design and construction of such projects involve more and more challenges, e.g., complex structural designs, complicated construction environments, etc. This research study aims to apply BIM (Building Information Modelling) to bridge projects to improve the efficiency and effectiveness of design and construction. Through the analysis of the characteristics of bridge projects and relevant, associated problems, a BIM-based solution to improving design and construction is developed, including conceptual design optimization, detailed design optimization, the optimization of construction sequences, construction scheduling, construction management, and construction process monitoring. Furthermore, a real-life bridge project is presented to demonstrate the feasibility and validity of the BIM-aided approach to design and construction. It is shown that BIM has the potential to improve the design and construction of bridge projects. It is expected that this research could contribute to the extensive application of BIM in mega-complex bridge projects to aid in design and construction in the future.

Keywords Bridge projects, Design, Construction, BIM

1. Introduction

In recent years, due to requirements stemming from developments in the global economy, more and more mega-bridges have been built, for example Hangzhou Bay Bridge (China) and Hong Kong-Zhuhai-Macau Bridge. The design and construction of this type of project is complex, involving complex structural designs, complicated building environments, etc. Conventionally, the design and construction of bridge projects is only based on 2D (two-dimensional) shop drawings and project managers’ experience. However, owing to the complexities of such projects, it is hard to determine design problems in advance only by using 2D shop drawings, and thus design problems commonly occur in construction sites. This leads to a high rework rate. Experience-based construction planning, on the other hand, is also not suitable for the construction of modern bridges, particularly when a large amount of
prefabricated components are involved. This influences not only construction time and cost, but construction safety. Meanwhile, management costs also increase since more management personnel are needed to solve associated problems. Therefore, it is important and necessary to ensure the constructability of a bridge design and the feasibility of the construction plan of bridge projects.

In order to improve the efficiency and effectiveness of the design and construction of bridge projects, some research studies have sought to introduce information technologies to this field. For example, Wu et al. [1] proposed a DES (Discrete Event Simulation)-based bridge construction project management system to aid in the time scheduling and the simulation of construction processes, considering resources and interdependencies between different tasks. Amongst them, BIM (Building Information Modelling) is regarded as a promising technology and approach. Chen and Shirole [2] surveyed the applications of BIM and information and automation technology in bridge engineering and management, and found that an information-centric bridge information supervision system has the potential to aid in the life cycle management of bridge projects, including parametric 3D (three-dimensional) modelling, 4D (four-dimensional) visualization, designs in detail construction drawing and health monitoring.

For the application of BIM in the design of bridge projects, specifically, Shim et al. [3] proposed an extensible information schema based on 3D, parametric modelling and simulation technologies, to enhance the visibility of bridge design schemes. Shin et al. [4] applied BIM to the analysis and design of a reinforced concrete bridge column by combining it with a parametric modelling mechanism. BIM is also introduced into the construction planning and management of bridge projects. For example, a 3D/4D CAD approach was used to aid in the modelling and scheduling analysis of a cable-stayed bridge [5], to achieve dynamic construction processes and intuitive analysis for large-scale bridge projects [6,7], to conduct the visual management and inquiry of construction schedules for highway bridge projects [8], to assist in the fabrication and geometry control of precast units for concrete box-girder bridges [9], to detect and amend the spatial conflicts of steel components and concrete abutments and optimize the installing and hoisting processes of prefabs in a steel bridge project [10], and to identify potential conflict problems and test construction plans in a cable-stayed bridge project [11]. Li et al. [12] also demonstrated the use of virtual prototyping (VP) in the simulation of construction processes and resource allocation to avoid collisions between construction machinery and elements and ensure the feasibility of the construction scheme. In summary, these research studies have made some useful attempts at adopting BIM-related technologies in various kinds of bridge projects, particularly to aid in the visualization and structural analysis of bridge design, the scheduling and visual control of bridge construction, and the production and control of prefabricated units, and it is believed that BIM will contribute to creating more efficient design and construction processes. Even so, BIM and relevant technologies are not well and extensively employed in bridge projects worldwide [13]. The use of BIM in bridge projects has only recently been tried and is still fragmented, focusing mostly on conflict detection, and scheduling and sequencing simulations. Few of these research studies address its application to resource allocation and safety management during construction, and health monitoring and maintenance in the operation stage.

BIM-related technologies, however, have been widely promoted and applied in building projects, particularly in developed countries or regions. For example, 3D/4D technologies were employed to aid in structural analysis and cost control analysis [14], construction planning and scheduling [15], and construction management [16-22]. BIM was also used to improve the design and construction processes of building projects [23]. VP technology was applied to the optimization of construction planning and processes [24,25], construction process management [26,27], construction safety management [28], life cycle management [29], etc. It has been proved that BIM can provide an effective support for design and construction as well as an effective collaboration and communication platform for different parties [23-29]. With the aid of BIM, design and construction rework is reduced, construction costs and time saved, and the quality of building projects also improved [24-27].

By referring to the successful application of BIM in building projects, this research attempts to propose a means for using BIM to improve the design and construction process of bridge projects and apply it to a long-span steel-box arch bridge project. The aim of this research study is to promote and extend the application of BIM in bridge projects. In order to successfully apply BIM to bridge projects, the characteristics of bridge projects and relevant problems are first analysed, and then the BIM-based solution developed. In the end, a real-life bridge project in Congo is presented to analyse the feasibility and validity of the BIM-aided design and construction solution.

2. Characteristics of design and construction of bridge projects

Most bridge projects are mega (long-span) and complex, involving various types of structural design. Additionally, bridge projects are always related to complicated construction environments and different
construction methods. In order to successfully apply BIM to bridge projects, the characteristics of the design and construction of bridge projects and relevant problems are analysed in detail as follows.

2.1 Complexity of structural design

In order to meet the requirements of structural stability, the design of a bridge project is usually complex with the involvement of a great amount of structural components, especially at certain joints. This often leads to collision problems, for example, between steel structural components. As mentioned above, it is difficult for designers to determine and remove such design problems in advance only by using 2D drawings, which, therefore, results in a high rework rate. Although some design problems can be identified, it is hard to make design modifications consistent and efficient using 2D design platforms. Besides this, the complexity of designs also leads to complex construction processes, such as complex construction sequences and resource allocation, which, however, are usually arranged based on project managers’ experience. It is difficult to ensure the feasibility of construction planning and, thus, problems relating to construction often occur in construction sites, causing rework, time and cost overruns, and safety problems.

2.2 Large amount of (bulky) prefabricated components

Both steel bridges and reinforced concrete bridges involve a large amount of prefabricated components, which may be produced on-site or at a prefabrication factory and then installed on-site. It is necessary to ensure the constructability of the design and control the production process of prefabricated components in detail. If prefabricated components cannot be installed due to a mismatch of their dimensions, the components would then need to be redesigned and reproduced. This leads to increased costs, especially for precast components that are hard to reutilize, and even the suspension of construction.

During the process of production, transportation and installation of large amounts of heavy and bulky prefabricated components, the following issues need to be considered. 1) How such components can efficiently be produced in prefabrication factories and transported to construction sites; 2) How to arrange an appropriate installation sequence for this kind of component; and 3) How to select the appropriate construction equipment required to lift heavy and bulky prefabricated components. All of these have a serious influence on the efficiency of production and the installation of prefabricated components; however, they usually depend on the project managers’ experience, for example, to determine the production methods, transportation routes, installation methods, and the amount and loading capacity of construction equipment. For these reasons, construction problems often occur in construction sites.

2.3 Uncertainty of construction environment

Bridge projects usually involve uncertain and complicated construction environments, e.g., crossing rivers, seas, valleys and tundra. Different bridge projects may involve totally different environments. In order to make construction processes smooth and safe, construction methods must be suitable for specific environments. This is why bridge projects have high requirements for their construction methods and construction management. However, the construction planning of bridge projects is usually based on project managers’ or engineers’ experience. Due to the diversity of bridge projects and the complexity of the construction environments, it is difficult for an engineer or project manager to ensure the feasibility of the construction planning for a new project. As a result, rework and safety problems appear during construction.

In addition, problems related to information exchanging and sharing among different parties are hackneyed and influence the efficiency of the construction industry [20].

With the above-mentioned characteristics of the design and construction of bridge projects, and associated problems in mind, in this research study, BIM is used to provide not only a design and construction optimization platform for designers, production and construction managers, and engineers, but an information integration and sharing platform for different parties involved in a bridge project.

3. BIM-based design optimization of bridge projects

Designing bridge projects includes a preliminary design and a detailed design. In order to integrate BIM within the design process of a bridge project, firstly 3D modelling needs to be carried out, that is, 2D shop drawings are transferred to 3D models. Then design optimization is carried out based on the 3D models. The BIM-based optimization process for the design of bridge projects mainly focuses on the modelling, analysis, detection, and feedback of the design. A BIM team collects shop drawings and builds relevant 3D models. At the same time, BIM technology is adopted to check design problems. If a problem is detected, it would be fed back to the BIM team and the project manager. If necessary, the relevant drawings are modified, remodelled, and searched until no problems are found. It is expected that all design problems would be detected
and solved prior to the commencement of construction by repeating the optimization process, in order to ensure the constructability of the design and reduce the rework related to the design. Note that the design of bridge projects is usually based on 2D drawings and 3D modelling is normally conducted by professional BIM modellers.

3.1 BIM-aided preliminary design

The purpose of the preliminary design of a bridge project is to determine the type of the bridge and its structural type, e.g., the layout of the bridge in the plan, elevation and section views, which concern the location, superstructure, and substructure of the bridge. Determining the type of a bridge usually involves comparing and selecting different conceptual design options. This may take a long time since it is often difficult for designers to communicate with owners and make a design match the surroundings only by using 2D platforms. By integrating BIM technologies, conceptual designs can be represented in a digital and parameterized manner. Figure 1 shows the BIM model of the preliminary design of a bridge project. With such a model, it is more convenient than before to compare different design options and examine their pros and cons. This is because BIM models can be better understood as well as adopted to produce the plan, elevation and section views of bridge projects. Besides from this, the digitization and parameterization related to BIM models also makes modifying the bridge design more convenient and therefore facilitates the selection of design options.

Moreover, using BIM models, an effective and efficient platform for communication and collaboration can also be provided for all interested parties (e.g., designers, owners) to evaluate the feasibility of design options. This could save a lot of time since it is easy to identify and meet owners’ needs.

Figure 1. The BIM model of the preliminary design of a bridge project

3.2 BIM-aided detailed design

Detailed design is the extension of preliminary design. The aim is to refine the integral or local structures of bridge projects, e.g., cross sections and reinforcement detailing, and analyse the feasibility of bridge structures. By seeking to accurately portray complex structures with a detailed design, BIM can provide a useful tool for structural optimization. Using initial BIM models, 3D modelling can be deepened by combining it with detailed design drawings; this process is called detailed modelling. Figure 2 shows the detailed structural model of a bridge project. Collision analysis can then be conducted and collision reports produced using BIM technologies. When collision problems are detected, a modification-remodelling-redetection cycle runs until all the problems are solved and the design of the bridge is determined. BIM makes the modification of designs more convenient than it was previously, since all components in BIM models are created on the basis of parameterized relations that ensure the consistency of the design modifications. Any modification to one component would lead to automatic changes in the other components related to that component, therefore reducing redundant work and errors to a large extent.

Figure 2. The detailed structural model of a bridge project

4. BIM-based construction optimization of bridge projects

Considering the complexity and large amount of bridge components, the aim of construction optimization is to ensure the feasibility of the construction plan and to improve the efficiency and management of the construction. Based on BIM models built at the design stage and the construction plan, construction processes are simulated visually to analyse the feasibility of construction sequences, and scheduling and resource allocation, and, furthermore, to optimize the construction plan. Figure 3 shows the BIM-based construction optimization process for bridge projects. Note that the simulation of construction processes is usually carried out by BIM engineers and construction managers, who are responsible for the evaluation and modification of the construction plan.
4.1 Optimization of construction sequences

By using BIM and simulation technologies, the 3D model of the bridge project is integrated with relevant construction methods to simulate the construction sequence of complex structures or prefabricated components. The feasibility and rationality of construction sequences can be tested by using such vivid process simulations. When a construction problem is identified, the relevant construction plan is modified and re-simulated until an appropriate construction plan is achieved. This makes construction processes smooth and ensures the quality and progress of bridge projects.

4.2 Optimization of construction schedule

The construction schedule may be simulated and optimized by using BIM and simulation technologies. Such simulations can be carried out using various time steps, e.g., days, weeks, and months, updated by combining the requirements of the construction, and adapted to compare different schedules and to help select the optimal one. By focusing on the critical segments of the construction, construction simulations may be conducted in detail, e.g., construction space arrangements, equipment allocation, material supplies, and component assembly. Similarly, the optimization of construction schedules is repeated in order to obtain the optimal schedule and resource allocation.

4.3 Optimization of construction management

From the above simulation and optimization of construction processes, potential problems related to construction can be identified and solved in advance. This changes the concept of construction management, from passive management, in which project managers wait for problems to occur on site, to proactive management, in which project managers detect and solve problems actively, therefore reducing both construction problems as well as simplifying management activities on site. Meanwhile, construction processes may be simulated virtually to guide real construction, and especially to help workers understand construction technologies and methods, collaboration, and potential safety problems. This not only reduces construction problems, but improves the efficiency of management. Therefore, BIM and simulation technologies have the potential to support the construction management of bridge projects and optimize management processes and activities.

5. BIM-based construction monitoring for bridge projects

As mentioned above, a bridge project involves a large amount of prefabricated components, most of which are bulky and heavy. When a structural analysis is conducted, the strain caused by the deadweight of the components must be considered, particularly for steel-structure arch bridge projects. Figure 4 shows the strain of a component during the installation of an arch bridge project. The aim is to ensure that each component can meet its design level and location after all the components are installed. However, due to deviations from the design or construction operations, it is difficult to make every component match with the design on site. As a result, there can be deviations between the design and what occurs with a component on site. Therefore, it is necessary for project managers to monitor and adjust such deviations in real time. This involves installing monitoring devices on site, comparing monitoring strain values with design strain values, and adjusting the dimensions of components or construction methods.
By adopting the BIM model of a bridge project, monitoring devices can be set up in the virtual environment to test relevant performance criteria until an appropriate setting solution is found. The design strain value of every component is also integrated within the BIM model and the relevant process simulation. Once the monitoring strain value of a component is obtained, it can be compared with relevant design values to determine whether the deviation is stable or not. If the deviation is unacceptable, the dimensions of the component or relevant construction method can be adjusted and tested by using BIM technology. An appropriate solution can be found with which to inform the real construction. This not only improves the accuracy of the monitoring value, but also assists in monitoring-related analyses and adjustments.

6. Case study

Loukouni Bridge in Project II of Congo State Route I, a landscape bridge, is a typical long-span steel structure arch bridge. Since it involves a large amount of prefabricated components, BIM technologies are being used to streamline construction processes and aid in the construction management in this project, including 3D modelling, design detection, construction simulation and analysis, and construction monitoring. This project is used in this research to evaluate the feasibility and validity of using BIM to improve the design and construction of bridge projects.

6.1 Design optimization

The application of BIM in the design of this project mainly involved scheme tests and collision detections, over two steps, namely, 3D modelling and design collision detection. The 3D model of the bridge was firstly built based on its design drawings and was used to support the design optimization and construction simulation. Figure 5 shows the 3D model of the bridge, and Figure 6 shows a detailed model of a structural component. Design collisions were then detected based on the above 3D model and project requirements, carrying out a detection for the whole bridge and some of the components. The detection process was automatically implemented by using a BIM software package. The components with collisions were highlighted and exported to produce collision reports. Therefore, it was convenient for the designers to observe these collisions and make necessary modifications.

Figure 5. The 3D model of Loukouni Bridge
Although the design of this project was not so complex, there were still design defects and collisions, especially detailed structural collisions, which would have been hard to find using traditional means of detection. In this project, three kinds of collisions or problems related to detailed structures were found in total. 1) During the 3D parameterized modelling of the bridge, it was found that there were several problems in the design drawings, for example, errors related to the dimensions and quantity of some components; 2) the joints of some columns and arch ribs did not fully match with each other; and 3) the width of some reserved welding seams could not meet the requirements of the relevant design criteria. As an example, Figure 7 shows one of the substandard welding seams.

By communicating with the designers, the shop drawings related to the design problems were modified. The relevant BIM models were also updated and then analysed again to detect design problems. Therefore, all of these problems were solved prior to the commencement of construction. Both the designers and the project manager thought BIM provided key support to the design of this bridge project.

6.2 Construction optimization

In the construction of this project, BIM technology was mainly applied to the simulation and analysis of construction processes, and the above BIM models were integrated with the construction schedule and methods. During the simulation, the project manager, general foreman and BIM modellers collaborated in identifying and solving construction problems. Firstly, a preliminary simulation was carried out by combining the preliminary construction plan and the BIM models. This stage focused mainly on an analysis of the consistency of the construction schedule with the design schedule. Based on the suggestions from the project manager and the general foreman, the original construction schedule was continuously improved. With the development of a detailed construction plan, a detailed simulation was then implemented to improve the construction schedule and sequence. Using an iterative simulation, an appropriate construction schedule and relevant construction methods were obtained. Figure 8 shows a detailed simulation of the construction process of the bridge project, which vividly demonstrates construction information such as...
the schedule, components and the actual completion of the work. Thirdly, the main construction equipment (e.g., suspension cable devices) were also simulated to analyse the installation methods of prefabricated components and the allocation of equipment. Figure 9 shows the operating process of a suspension cable device. This helped determine the supply schedule of prefabricated units, and the setting and operation of relevant equipment.

Such simulations will also be used to train the site workers, who are local labourers who do not have rich experience, when the real construction commences. In order to help them better understand the construction methods, the surrounding terrain and construction machinery were added to the simulation of the process, which was then also rendered. Figure 10 shows the rendered simulation of the construction process of this bridge project. The project manager believed that the simulation of the process would provide a powerful means of support for the construction schedule as well as the management of the construction and safety training in this project.
6.3 Construction process monitoring

The construction monitoring for this project includes the location and strain of arch rib components, the strain of columns connecting the bridge deck with the arch rib, the strain of steel-box beams, and the strain of the bridge deck. Each aspect of the monitoring requires a large amount of monitoring points to be installed. For example, there are as many as 24 monitoring points for the lifting of the columns. The BIM model was used to help in the configuration of these monitoring points. Figure 11 shows the monitoring points for the columns above the arch rib of this bridge. Additionally, the design location and altitude of each point was integrated into the BIM model. Once construction starts, this can be used in the comparison of the monitoring values with the design values. If the deviation is unacceptable, the project manager has planned to use BIM technology to test different solutions.

7. Discussion

By using BIM in this project, which focuses on the detection of collisions and the analysis of design, the simulation and optimization of construction processes, and construction monitoring, it is shown that BIM has the potential to optimize the design and construction of bridge projects. By interviewing the project manager and the foreman, it is shown that there is belief that BIM can improve the efficiency of the design and construction in this project, although the project has not yet been completed.

At the same time, the use of BIM in this bridge project was not so smooth. The project participants, particularly site staff, were not familiar with BIM, therefore it was difficult for them to collaborate well with the BIM team on the BIM. This influenced the performance and progress of the BIM implementation. In order to solve this problem, some training sessions related to BIM were offered to the project team and site workers.

In addition, a questionnaire survey was conducted concerning the progress of this project to study the perspective of participants in bridge projects towards BIM. The respondents included 10 project managers (or assistant project managers), 2 designers and 33 engineers. Based on their responses, it was found that most of them only considered BIM as a display tool and some of them had no idea about BIM. Therefore, the application of BIM in bridge projects needs to be continuously promoted and attempted again and again.

8. Conclusion

By analysing the characteristics of bridge projects and associated problems, this research develops a BIM-based solution to improving design and construction, and applies this solution to a real-life case. It is shown that BIM has the potential to improve the efficiency and effectiveness of the design and construction of mega-complex bridge projects. It is expected that this research can provide a successful example for the promotion of the application of BIM to bridge projects. However, since participants in bridge projects lack BIM knowledge, the progress and quality of implementing BIM may be affected. Thus, it is necessary to provide appropriate training on BIM for each party when BIM is employed in a bridge project.

The quality of the BIM implementation in this case, additionally, was only evaluated using a qualitative method, i.e., based on the project manager's experience. This may not be enough to verify the effect of BIM on bridge projects. Therefore, some quantitative methods will be developed and employed to evaluate its performance in future research.

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