

Building Information Modeling for Whole-Life-Cycle Bridge Management

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Abstract. As bridge construction expands and existing bridges age, fragmented information across design, construction, and operation has become a major obstacle to refined bridge management. BIM provides a shared digital model for organizing geometry, materials, construction records, inspection information, and maintenance data within one framework. Based on recent research and engineering case studies, this paper reviews the application of BIM in the main stages of bridge projects. In the design stage, BIM is mainly used for parametric modeling, three-dimensional coordination, and conflict checking. In the construction stage, it supports 4D scheduling, visualized technical handover, site coordination, and safety-risk identification. In the operation and maintenance stage, BIM helps connect inspection records, monitoring data, defect descriptions, and maintenance decisions at the component level. The paper also summarizes the practical benefits of BIM in improving information continuity, management efficiency, and decision support. Meanwhile, several challenges remain, including incomplete standards, limited interoperability, model updating, and organizational implementation. Future bridge management is expected to further integrate BIM with digital twins, the Internet of Things, and artificial intelligence.

Keywords: BIM; bridge management; operation and maintenance; digital twin; information continuity.

1. Introduction

Bridge construction is an important part of transportation infrastructure. Since bridge projects have a longer construction period, involve a large number of people, and exhibit complicated structural behavior, they need constant transfer of information between stages, organizations, etc., for repeated inspections, repairs, and strengthening during their use. Traditional bridge management practices rely mainly on 2D drawings, static reports, and fragmented information records. Thus, designs, constructions, and maintenance records are usually kept separately. So information reuse is poor, problems are hard to trace back, and the team fixing it mostly relies on experience to judge if something's broken since the parts' characteristics, construction differences, and repair history aren't passed down fully [1-4]. From a whole-life-cycle perspective, bridge management should be regarded as a closed-loop process involving early decision-making, design, construction, delivery, inspection, maintenance, and performance evaluation. Otherwise, information loss in earlier stages may lead to greater management difficulties in later stages.

Building Information Modeling (BIM) organizes geometry, materials, construction procedures, inspection records, and operation data in a parametric digital model, providing a shared data foundation for whole-life-cycle bridge management. Recent studies show that bridge BIM has evolved from simple three-dimensional expression to parametric design, analysis linkage, and scheme comparison; from isolated construction modeling to integration with four-dimensional (4D) scheduling, extended reality (XR), and site coordination; and from static archives to scan-based reconstruction, monitoring integration, and digital-twin-oriented maintenance [2-6]. Current research generally follows two paths: forward application in new projects and reverse modeling for existing bridges. Both aim to eliminate information islands and improve quality, efficiency, and resilience throughout the service life.

2. BIM applications in the major stages of bridge engineering

2.1. Design stage

In terms of the design part, BIM mainly expresses itself through parametric form and 3D collaboration. In comparison to traditional 2D drawings, BIM modeling can describe the bridge span, girder section, substructure, prestressed duct, reinforcement, etc., in a more graphical and parametric way so that designers can verify geometric relationships, dimension constraints, as well as attribute information from one unique model. For cable-stayed bridges, cable-stayed piers, denser Statistical Process Control (SPC) joints, it makes it easier on the eye to spot clashes and detail conflicts before they get too big, resulting in less rework down the road. Parameter-driven modeling can allow for quick changes to the types of bridges, span combinations, family components, quantity, and it's very useful if route, structure, electromechanical, landscape, and construction need to be coordinated within one environment.

In more recent engineering studies, it is evident how much BIM has been used for designs. Jiang et al. established the parametric family of continuous beam components and main construction machinery at the Caodian-Shangqiu section of the Xiongan high-speed railway, using it for layout design of prestressed ducts and conflict checking with reinforcements and then improving the reusability of the model, minimizing the conflicts in congested places [7]. Wu noted that the parametric bridge BIM is going beyond just a first draft model; it is going into front-end design where rule-based parametric links go to analysis on components, schemes, and perform checks on concepts [8]. These studies indicate that BIM for bridges is more than a visual representation. It is also a place to organize design know-how and speed up other iterations, and build a standard library of components that can be used again for easier construction and maintenance tasks in the future.

2.2. Construction stage

The construction stage is one of the phases in which BIM can generate significant practical value. During the construction process, full-process technical control can be carried out, and its control technical route is shown in Fig. 1. Bridges usually have a lot of concrete and cantilevers, casting supports, segments, lifting, and road diversion, all of which require working from height. If project teams rely solely on 2D drawings and written briefings, it may be difficult to understand construction sequences and spatial relationships on site. Adding a construction model with time can make project teams create a 4D simulation, and they can simulate the sequence logic, resource input, equipment path, temporary work, etc. They can find some risks in an early stage by doing this kind of simulation and improve the site organization [3,9]. The same model can also be linked with quantity takeoff, material planning, and field records to improve resource allocation and reduce rework.

In practice, bridge BIM is moving from static simulation to immersive and interactive management. Alhady et al. developed an integrated Building Information Modeling and extended reality (XR) workflow for the El-Merghani Bridge in Egypt that integrated road geometry, bridge components, quantities, and schedule information, and then extended the model with Primavera P6 for 4D planning. Their results show that the workflow provided engineers and owners with an interactive virtual reality (VR) and augmented reality (AR) environment, improved communication, and helped identify design-construction deviations before execution [9]. Jiang et al. likewise show that parametric bridge models can directly support simulation of critical procedures and visualized technical handover in complex construction zones [7]. For bridge projects with tight schedules and overlapping operations, BIM therefore works best not as a display model, but as an executable carrier for schedule control, quality checkpoints, and safety-risk identification.

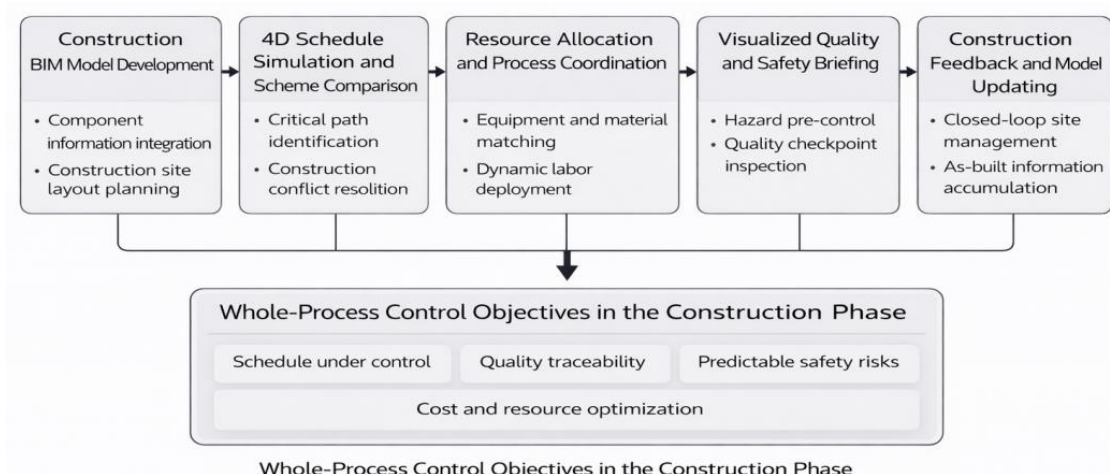


Fig. 1. BIM-based technical route for whole-process control during bridge construction.
(Photo credit: Original).

2.3. Operation and maintenance stage

At the operation and maintenance stage, BIM mainly supports asset information integration, condition perception, defect description, and maintenance decision-making. Bridges remain in service for long periods and gradually develop cracks, scaling, reinforcement corrosion, bearing damage, expansion-joint deterioration, and local deformation. If design files, completion records, routine inspections, special reports, and monitoring data cannot be organized in a unified way, a continuous information chain for maintenance cannot be formed. Byun et al. proposed a BIM-based bridge maintenance system built on a maintenance data schema and an information system, embedding diagnosis, residual life, and asset value into the management process and validating the prototype on an actual bridge in Korea [1]. Their work shows that BIM can serve as a structured carrier for maintenance information and make inspection, evaluation, repair, and value assessment traceable at the component level.

With the development of scan-based modeling and sensor monitoring, bridge BIM is evolving from a static archive model into a dynamic operation model. Kwon et al. proposed an Industry Foundation Classes (IFC)-based BIM health-monitoring framework and verified an artificial-neural-network method for anomaly detection on an in-service cable-stayed bridge in Korea, showing that monitoring data can be linked to specific BIM objects for more direct abnormality recognition and maintenance judgment [2]. Mohammadi et al. use TLS - PC and an information model of BIM along with DSS to prioritize component scores in the Werrington Bridge, NSW, Australia, and also prioritize strategy for repair, giving more objective reasons toward budget allocation and maintenance. Existing bridges, in particular where there is an incomplete archive, can be analyzed through workflows combining point clouds, models, and component attributes, which would help to supplement what's missing and document digitally [10].

3. Benefits and challenges

3.1. Practical benefits

From a whole-life-cycle perspective, BIM technology provides three main benefits for bridge management. Firstly, it can make the information continuous. Design models, construction records, and operation data can be integrated into a unified logical framework, reducing information duplication and loss. It can also be traced back for checking with reviewing technology [1,3]. The second benefit is better management. And in terms of doing a parametric iteration around the design, 4D simulation and visual briefing onsite, and defect tracking at a component level for operation, all these help shorten communication linkages as well as costs related to coordinating different

disciplines [7,9,11]. The third benefit is better decision-making. Use the model for checking: the model makes it possible that, with BIM, managers could choose alternatives (risk ranked) when making a maintenance plan. And their choice is decided on the basis of supporting data and not solely on experience [2-4, 12]. BIM, in this sense, is not just a piece of software but a way to organize and collaborate on information throughout the lifecycle of a bridge.

3.2. Key technical challenges

BIM has many obvious benefits, but further use of the entire life cycle of bridges still has some problems. Among these are bridge design tools, analysis software, scan-based modeling packages, BMSs, monitoring systems; there are large differences which mean cross-platform interoperability is still the key constraint [3-4, 12]. Bridge BIM standards are also behind in terms of practice: component coding, property sets, methods for describing defects, Limit of Detection (LOD) levels, and depth required for delivery have not been completely unified yet, so it's hard to pass things down smoothly between organizations. And bridges are in many places, with long lines, and a lot of parts. During operation, it's light, mobile, and constantly updating. It also requires a lot of information about the model for data and collaborating with organizations [1,5]. Without clear updating responsibilities and multidisciplinary support, the model will be out of date as soon as it is handed over and thus fails to maintain itself for a long time.

4. Conclusion

In short, BIM will help bridge construction progress by phases of projects to guide all through their lifecycles. In terms of designing, it can be expressed and optimized through parametric modeling and quick schemes. The construction phase helps out the site organization, ensuring safety for 4D sim and XR interaction/visualization during handover. For operation and maintenance, it's very much intertwined with surveillance and scanning of bridge systems, as well as digital twin technology that creates a constantly updated information system about all information regarding the parts, what kinds of defects they are having, and then deciding which one should be fixed first. Recent studies and engineering practices show that the real value of BIM lies not only in 3D visualization, but also in continuous data transfer, multi-stakeholder collaboration, and joint decision-making throughout the whole life cycle of bridges.

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