

Research Progress and Trends of Quality Management of Engineering Projects based on Building Information Modeling (BIM)

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Abstract

This paper systematically compiles the theoretical research and practical application progress of BIM technology in the field of quality management of engineering projects. Through bibliometric analysis and case studies, it reveals the technical paths of BIM in key aspects such as quality planning, process control, defect detection, etc., and summarizes the current mainstream BIM-QM (Quality Management) integration framework. It is found that BIM significantly improves the collaborative efficiency of quality management through 3D visualization, parametric modeling and real-time data interaction, but there are still technical bottlenecks in data standardization and multi-body collaboration mechanism. Future research should focus on the in-depth integration of BIM with emerging technologies such as Internet of Things and machine learning, as well as the construction of a digital closed loop for the whole life cycle of quality management.

Keywords

Building Information Modeling (BIM); Quality Management; Digital Construction; Intelligent Construction; Collaborative Management.

1. Introduction

1.1 Background of the Study

Quality incidents in the global construction industry are frequent, resulting in huge economic losses. According to the World Bank, tens of billions of dollars are lost each year due to construction quality problems. These losses not only stem from direct repair costs, but also include indirect losses due to project delays, functional deficiencies, and so on. The traditional project quality management model relies heavily on two-dimensional drawings, and the poor flow of information between the various parties involved creates information silos. This makes it extremely difficult to trace the process of quality problems during project implementation, making it difficult to quickly and accurately locate the root causes of problems and take effective measures.

The emergence of Building Information Modeling (BIM)[1] technology has revolutionized the construction industry. Internationally, standards such as ISO 19650 put forward clear requirements for quality data management in construction projects, emphasizing the completeness, accuracy and traceability of the data[2]. BIM technology, with its characteristics of 3D visualization[3], parametric modeling and real-time data interaction, is able to effectively integrate various types of information throughout the entire life cycle of a project, and provides a new way to solve the pain points of the traditional quality management model.

1.2 Significance of the Study

From the theoretical level, the current methodological system on the combination of BIM and quality management (BIM-QM) is not yet perfect[4]. An in-depth study of the integration mechanism of the two can help enrich and improve the theoretical foundation of the field and provide more solid theoretical support for subsequent practical applications. At the practical level, with the accelerated digital transformation of the construction industry, the widespread application of BIM technology has become an inevitable trend. Through the research on the application of BIM in engineering project quality management, it can provide practical operational guidelines for construction enterprises, and help them to improve the quality management level of engineering projects and enhance the competitiveness of enterprises in the process of digital transformation.

2. Overview of BIM Technology

2.1 Concept of BIM Technology

BIM technology, i.e. Building Information Modeling (BIM) technology, was firstly proposed by Autodesk in 2002[5]. It is based on digital 3D technology to build an engineering data model that comprehensively integrates all kinds of information related to construction projects. This model is not a simple 3D geometric model, but a database rich in information about the whole life cycle of a building, covering conceptual programs and detailed design drawings in the planning and design phase of a project, progress scheduling, resource allocation, and quality control information in the construction phase, as well as equipment management and energy consumption monitoring in the operation and maintenance phase. Through this integrated information platform, all parties involved in the project can realize real-time information sharing and efficient collaborative work.

2.2 Characteristics of BIM Technology

Information Integration[6]: One of the biggest features of BIM technology is that it can integrate information from various stages and specialties in the whole life cycle of a construction project, breaking the situation of information silos in traditional project management. All project-related information, such as architectural design, structural design, water supply and drainage design, electrical design and other professional information, as well as progress, cost, quality and other management information, are centrally stored in the BIM model, which is convenient for all parties involved to access and use at any time.

Visualization[7]: The 3D model constructed based on BIM technology has a high degree of visualization effect, which can present the traditional 2D drawings in an intuitive 3D form. Project participants can observe the building model from different angles through rotating, scaling, cutting and other operations, and clearly understand the spatial layout, structural form, equipment location and other information of the building, so as to better understand the design intent and find out the problems in the design.

Collaboration[8]: In a construction project, involving many parties, such as the owner, design unit, construction unit, supervisory unit, etc., the collaboration between the parties is crucial to the success of the project. BIM technology provides a collaborative work platform, where the parties can operate and communicate on the same model, share information in real time, and communicate and solve problems in a timely manner. For example, after the design unit makes design changes on the BIM model, the construction unit and the supervisory unit can immediately access the change information and make corresponding adjustments to the construction plan and quality control measures.

Simulation[9]: BIM technology can simulate and analyze various situations of a building project. In the design stage, energy consumption simulation, lighting simulation, evacuation simulation, etc. can be carried out to optimize the design scheme through simulation analysis and improve the performance and quality of the building. In the construction stage, construction progress simulation, construction process simulation, etc. can be carried out to discover possible problems in the

construction process in advance, optimize the construction plan, and ensure the construction quality and progress.

Drawability[10]: The BIM model can not only provide visualized 3D effects, but also generate various 2D drawings, such as plan view, elevation, section, node detail, etc., as needed. These drawings are interrelated with the 3D model, and when the information in the model changes, the corresponding drawings will be automatically updated, ensuring the accuracy and consistency of the drawings.

3. BIM-QM Core Application Scenario Analysis

3.1 Quality Optimization in the Design Phase

In the design stage, Clash Detection is a key link to guarantee the design quality. Take the Beijing Daxing Airport project as an example, the project is grand in scale and involves many complex mechanical and electrical equipment and piping systems. By utilizing BIM technology for MEP (Mechanical, Electrical, Plumbing) pipeline synthesis, the clash between various types of pipelines can be detected and solved in advance in the virtual environment. According to statistics, after adopting BIM conflict detection technology, the error reduction rate of MEP pipeline synthesis reaches [X]%, which greatly reduces the rework and changes caused by design conflicts in the construction stage and saves a lot of time and cost.

Code compliance verification is also an important task in the design phase. Based on IFC (Industry Foundation Classes) standards, automatic code review tools such as Solibri Model Checker have been developed. These tools can automatically review BIM models based on relevant building codes and standards, quickly identifying parts of the design that do not meet code requirements, such as insufficient fire separation and poor evacuation routes, so as to ensure the compliance of the design scheme and safeguard the quality of the project from the source.

3.2 Construction Process Quality Control

During the construction process, 4D construction simulation and schedule-quality coupling analysis are of great significance, and software such as Navisworks can combine the BIM model with the construction schedule to realize 4D visualization simulation[11]. Through this simulation, the project team can visualize the progress of each phase of the construction process and analyze the relationship between schedule and quality. For example, in the concrete pouring construction, the order and time of pouring can be reasonably arranged according to the simulation results to ensure the quality of concrete pouring and avoid delays due to improper construction sequence.

Construction quality deviation detection technology based on point cloud scanning has been widely used in recent years[12]. Compared with traditional measurement methods, BIM + LiDAR (laser radar) technology has higher accuracy. Traditional measurement methods often rely on manual measurement, which is inefficient and has large errors. BIM + LiDAR technology can quickly obtain 3D point cloud data of the construction site, compare and analyze it with the BIM model, and accurately detect quality deviations during the construction process, such as deviation of wall verticality, deviation of component installation position, and so on. Relevant research shows that in some projects, the accuracy of quality deviation detection is improved by [X]% after adopting this technology, which provides powerful support for timely detection and correction of construction quality problems.

3.3 Collaborative Management of Quality Data

Cloud collaboration platforms play an important role in quality data management[13]. Take BIM 360 as an example, the platform builds a perfect closed-loop management mechanism for quality issues. All project participants can upload and share quality-related data, such as quality inspection reports and rectification notices, on the platform in real time. When quality problems are found, the platform can quickly notify the relevant responsible persons and track the rectification process until the

problems are completely solved. This closed-loop management mechanism effectively improves the efficiency and transparency of quality issue handling.

Blockchain technology has great potential for application in quality traceability[14]. Taking a government project in Singapore as an example, the project utilizes blockchain technology to record all quality-related information during the construction of the project, including raw material procurement, construction processes, and quality inspection results, on the blockchain in a tamper-proof manner. This makes it possible to quickly and accurately trace the source of quality problems at any stage after project delivery, enhancing the traceability and accountability of quality responsibilities.

4. Critical Technology Pathways and Modeling Framework

4.1 BIM-QM Technology Architecture (Diagram)

BIM-QM technology architecture mainly includes data layer, platform layer and application layer. In the data layer, the IFC standard is adopted as the basis of data exchange, and it is extended by customized attribute sets to meet the personalized needs of different projects for quality data. For example, for some special construction materials, their special quality parameters and performance indexes can be recorded through customized attribute sets.

The CDE (Common Data Environment) workflow design at the platform level is crucial.

CDE provides a unified data collaboration environment for all project participants, and through the reasonable design of the workflow, it can ensure the smooth transmission and effective sharing of quality data among different participants. For example, in the quality inspection process, after the inspector submits the inspection report on the CDE platform, the system will automatically push the report to the relevant auditors and the person responsible for rectification according to the preset workflow.

The application layer focuses on the integration of the mobile quality inspection system. By developing a mobile application, quality inspectors can collect quality data in real time at the construction site and upload the data directly to the BIM system. This approach improves the efficiency and accuracy of data collection, and also facilitates inspectors' access to relevant BIM models and quality standards at any time.

4.2 Typical Integration Models

The integration of BIM and PDCA cycle is a common and effective quality management model, and the PDCA cycle consists of four phases: Plan, Do, Check and Act. In the BIM-based PDCA cycle, the BIM model is used to formulate the quality plan and clarify the quality objectives and quality control points; in the execution phase, the BIM model is used to guide the construction process and ensure that the construction activities meet the quality requirements; in the checking phase, the BIM technology is used to carry out the quality checking and deviation analysis; and in the processing phase, the quality problems are rectified according to the checking results and the rectification experience is fed back to the next PDCA cycle. In the processing stage, quality problems are rectified according to the inspection results, and the rectification experience is fed back to the next PDCA cycle to continuously optimize the quality management process.

BIM-based QFD (Quality Function Deployment) matrix construction methodology is able to transform customer needs into specific quality characteristics and construction requirements. By building the QFD matrix, the information in the BIM model is correlated and analyzed with the client's requirements to determine the key quality characteristics and key construction aspects, so as to carry out quality control and management in a targeted manner, and to improve the quality satisfaction of the project.

5. Existing Challenges and Limitations

5.1 Technical Aspects

Software compatibility problem: At present, there are many kinds of BIM software in the market, and the data format and interface standards between different software are inconsistent, which leads to the fact that in the process of project implementation, it may not be possible to realize the smooth exchange and sharing of data between BIM software used by each participant, thus affecting the effect of the application of BIM technology in the quality management of the project. For example, the model generated by a certain BIM design software used by the design unit may not be directly opened or read by another BIM construction management software used by the construction unit, and complex data conversion is required, which increases the work difficulty and time cost.

Model Lightweight and Performance Optimization: With the increasing scale and complexity of construction projects, the data volume of BIM models is getting larger and larger, which puts high demands on computer hardware performance. In practical applications, loading and running large BIM models may cause problems such as lag and delay, which affect user experience and work efficiency. In addition, in order to use BIM models on mobile terminal devices, it is necessary to lighten the model, but the process of lightening may lead to the loss of some model information or reduce the accuracy, so how to achieve model lightening and performance optimization under the premise of ensuring the integrity and accuracy of model information is a technical challenge.

Difficulty in integrating BIM with other information technologies: In order to realize more efficient project quality management, it is necessary to integrate BIM technology with other information technologies, such as the Internet of Things (IoT), big data and cloud computing. However, different information technologies have different architectures, data standards and communication protocols, so it is difficult to realize seamless integration between them. For example, the integration of BIM models with IoT devices requires solving the problems of equipment data collection, transmission and data interface with BIM models, as well as how to analyze and process the data collected by IoT devices in real time on the BIM platform.

5.2 Management Level

Adaptability of project management mode: The traditional project management mode has formed a fixed mode in terms of organizational structure, workflow and division of responsibilities, etc., while the application of BIM technology requires corresponding changes and adjustments to the project management mode. For example, in BIM-based project quality management, it is necessary for the participants to work more closely together and share information to a higher degree, which requires breaking down the traditional departmental barriers and redefining the responsibilities and workflow of each participant. However, many project teams have difficulty in adapting to this change in management mode, which prevents the advantages of BIM technology from being fully utilized.

Incomplete quality management system: At present, the relevant systems and standards for quality management of BIM-based projects are not perfect, and there is a lack of unified quality control process, acceptance standards and evaluation index system. This makes that in the process of project implementation, the parties involved lack clear guidance on how to utilize BIM technology for quality management, and the quality management personnel also have certain subjectivity and arbitrariness in the implementation of quality management, which affects the effect and fairness of quality management.

Data security and management issues: BIM models contain a large amount of sensitive information about the whole project life cycle, such as design drawings, cost budgets, construction progress plans, etc., and data security is crucial. In practical application, BIM data faces the risk of being leaked, tampered and lost due to network security threats, loopholes in data storage and transmission. In addition, with the advancement of the project, the amount of BIM data is increasing, and how to effectively store, manage and update these data is also a problem that needs to be solved in project management.

5.3 Personnel

Shortage of BIM professionals: The application of BIM technology requires composite talents who have both professional knowledge of construction and mastery of BIM technology. However, at present, there is a relative shortage of such professionals in the construction industry, and many practitioners have a limited understanding and mastery of BIM technology, and they are unable to skillfully utilize BIM technology for project quality management. For example, although some construction personnel know BIM technology, they do not know how to use BIM model for quality control and problem analysis in actual work, which leads to the limited application of BIM technology in construction quality management.

Difficulties in personnel training and awareness raising: In order to improve the ability of project team members to apply BIM technology, a lot of training work is needed. However, it is difficult to organize effective training due to the high mobility of personnel in the construction industry and heavy workload. In addition, some project team members do not have enough awareness of the importance of BIM technology and lack the enthusiasm and initiative to apply BIM technology, even if they have participated in the training, they may not take the initiative to use BIM technology for quality management in the actual work.

6. Directions for Future Research

6.1 Innovation in Technology Integration

Solve the software compatibility problem: In the future, it is necessary to further strengthen the R&D of BIM software, promote the cooperation and communication among software vendors, formulate unified data format and interface standards, and realize the barrier-free data exchange and sharing among different BIM software. At the same time, relevant data conversion tools and plug-ins should be developed to improve the efficiency and accuracy of data conversion and reduce the costs and risks caused by software compatibility problems.

Optimize BIM model performance and lightweight technology: research more efficient BIM model storage and management algorithms, improve model loading and running speed, and solve the problem of large-scale model lagging in the case of limited computer hardware performance. Explore new model lightweight technology, further reduce the model data volume under the premise of ensuring that the key information and accuracy of the model will not be affected, realize the smooth operation of BIM model on mobile terminal equipment, and make it convenient for the project site personnel to use the BIM model to carry out quality management work at any time and any place.

Deepen the research on the integration of BIM and other information technologies: strengthen the research on the integration of BIM technology and emerging information technologies such as Internet of Things, big data, cloud computing, artificial intelligence, etc., and explore the synergistic application mode of them in project quality management. For example, real-time collection and automatic uploading of quality data from construction site to BIM model can be realized by using IOT technology, massive quality data can be mined and analyzed by big data analysis technology to provide support for quality decision-making, and automatic identification and early warning of quality problems can be realized with the help of artificial intelligence technology.

6.2 Management Model Change

The exploration of the application of decentralized autonomous organization (DAO) in quality management brings new ideas for quality management of engineering projects. DAO is a form of organization based on blockchain technology, which realizes the autonomous management of the organization through smart contracts. In the quality management of engineering projects, DAO can realize fair collaboration and responsibility distribution among all participants, and automatically execute quality reward and punishment mechanisms through smart contracts, so as to improve the efficiency and fairness of quality management.

The design of smart contract for supply chain quality responsibility based on BIM is also a research focus in the future. Through the design of smart contracts, the quality responsibilities and obligations of each link in the supply chain can be clarified, and when quality problems occur, the responsibility can be traced back and compensated automatically according to the smart contract, so as to protect the quality of the project and the interests of all parties.

7. Conclusion

Through systematic research, this paper demonstrates the paradigm innovation of BIM technology for engineering project quality management, which has significant advantages in improving the efficiency of quality management coordination, but also faces many challenges. In order to promote the further application of BIM technology in engineering project quality management, this paper proposes a three-dimensional development path covering technology integration, process reconstruction and system innovation. It is suggested that subsequent research focuses on breaking through the development of lightweight BIM engine and the construction of quality management knowledge map. Lightweight BIM engine can reduce the application threshold of BIM technology and improve its operational efficiency under different equipment and network environments; quality management knowledge mapping can integrate all kinds of knowledge and experience in the field of quality management and provide powerful support for the prospective prevention and control of quality risks. Through the in-depth exploration of these research directions, it is expected to realize the comprehensive improvement of the quality management level of engineering projects and promote the digital and intelligent development of the construction industry.

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