Construction and Application of a BIM-based Progress Risk Management System for Quality Inspection and Evaluation in Hydropower Engineering Projects

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Abstract. Addressing the issue of project delay risks arising from the lagging quality inspection and assessment progress in hydropower projects, this study proposes a BIM-based quality inspection and assessment progress risk management system. By integrating three-dimensional models, quality inspection and assessment data, and construction progress information, the system enables dynamic risk analysis and early warning. Adopting a layered architecture design, the system encompasses the data layer, business layer, and presentation layer. It utilizes model lightweighting, unified coding, and multi-source data association technologies to conduct real-time comparisons between the completion rates of quality inspection and assessment and construction progress. Through the use of discrepancy coefficients and threshold values, the system determines the risk of delays. Combined with depth-first search algorithms and adjustment factors, the system can dynamically optimize the planning of remaining inspection and assessment tasks. A case study of a pumped storage project in Gansu Province has verified the effectiveness of this system in improving the efficiency of quality inspection and assessment and reducing the risk of delays, providing digital decision support for quality management in hydropower projects.

Keywords: BIM, quality inspection, hydropower engineering, risk analysis

1 Introduction

The concept of Building Information Modeling (BIM) was proposed by Chuck Eastman from the United States in 1975. He posited that BIM integrates all information throughout the entire lifecycle of a construction project, combining geometric model data, functional requirements, component performance, as well as construction schedules and maintenance management processes[1].With the rapid development of information technology and the comprehensive digital transformation of the engineering industry, BIM technology has demonstrated increasingly broad application prospects in the project management of hydropower engineering[2].By leveraging BIM, on-site project managers can more intuitively grasp the overall layout, structural details, and

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construction progress of hydropower projects. However, in practical applications, BIM still lacks effective data integration and sharing mechanisms across multiple disciplines and departments[3].

In hydropower projects, quality inspection and evaluation serve as the core of on-site quality management, playing a critical role in ensuring construction quality[4]. On-site managers must promptly conduct inspections and assessments after the completion of each process, unit project, subproject, division project, and unit engineering to verify that the quality at each stage meets design requirements. The effective execution of this workflow not only directly impacts the overall project quality but also influences construction progress and cost control. If quality inspection and evaluation lag significantly behind on-site construction progress, subsequent engineering delays may occur, leading to extended timelines, economic losses, and adverse effects on overall project benefits.

Existing quality inspection and evaluation systems based on BIM technology can dynamically display real-time quality inspection statuses for various project components, including qualification rates and quantities. However, they still exhibit notable shortcomings in utilizing and deeply analyzing progress data[5]. Current systems fail to integrate actual construction progress information with quality inspection data for in-depth mining and analysis. This limitation hinders the timely identification of potential issues, such as excessively low completion rates of quality inspections relative to construction progress, thereby preventing accurate assessment of project delay risks and posing significant challenges to on-time project delivery[6].

To address these issues, this study proposes a BIM-based risk management system for quality inspection and evaluation progress in hydropower projects. By introducing advanced algorithms and models, the system can analyze deviations between quality inspection progress and actual construction progress in real time, accurately assess project delay risks, and visualize results. This provides timely and accurate decision-making support for project managers, offering new ideas and methods for quality management in hydropower projects. To further validate feasibility, the system has been applied to a pumped storage power station project in Gansu Province.

2 Construction of the BIM-based Quality Inspection and Evaluation Progress Risk Management System

2.1 Project Overview and Requirements

The pumped storage power station project in Gansu Province faces tight schedules, large workloads, and involvement from multiple participating units. Given the project's importance and complexity, the construction entity proposed the following requirements:

(1)Enhance control over quality inspection and evaluation completion: Ensure the timeliness and accuracy of quality inspections through systematic management.

(2)Track deviations between actual progress and quality inspection completion: Identify deviations in real time through data collection and analysis, enabling prompt corrective actions.

(3)Implement risk management for quality inspection completion: Identify potential risks in advance through risk assessment and early warning mechanisms, enabling refined management.

2.2 System Architecture

Based on the practical needs of the pumped storage power station, a BIM-based quality inspection and evaluation progress risk management system was developed, integrating quality inspection management with on-site construction progress. The overall architecture is as follows(see Figure 1):

(1)Presentation Layer

The presentation layer provides a unified application portal via PCs, large visualization screens, and mobile devices. This portal grants access to integrated displays, quality inspection management, and progress management systems, serving as a platform for effective communication among project stakeholders.

(2)Business Layer

Leveraging collected data and technologies such as BIM, IoT, big data, deep search algorithms, matrix data acquisition algorithms, and merge-aggregation algorithms, this layer enables 3D visualization of project management data, deep data mining, multi-dimensional statistical analysis, and real-time alerts. It facilitates efficient data linkage across horizontal departments and vertical hierarchies, aiding on-site managers in scientific decision-making, improving lean management, and enhancing project efficiency.

Additionally, the business layer provides foundational services for the construction management information platform, connecting the data and presentation layers. These services include a portal system, unified identity authentication, single sign-on, data exchange, application management, content management, and integration with third-party data interfaces.

(3)Data Layer

The data layer primarily handles the storage of foundational and operational data, including quality inspection databases, progress databases, and model databases.

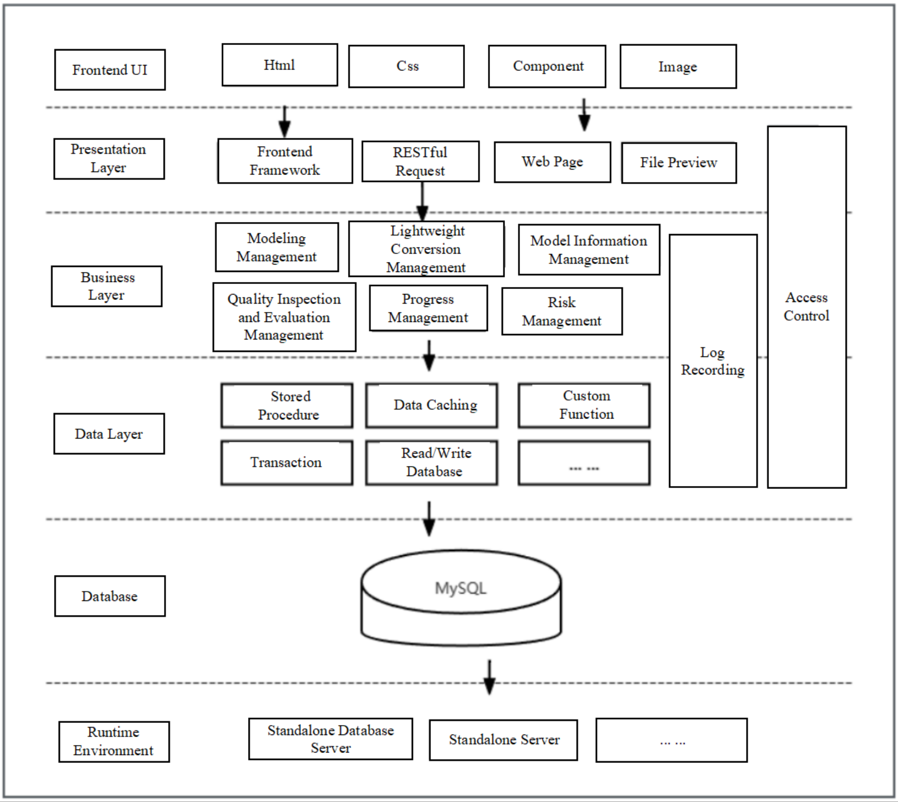

Fig. 1. Overall System Architecture

2.3 System Data Integration and Analysis Methods

The BIM-based risk management system for quality inspection and evaluation progress in hydropower projects centers on project division, integrating 3D BIM models, quality inspection data, and progress data to achieve effective data integration and deep analysis. The specific integration and analysis methods are as follows:

(1)Model Construction: Collect modeling materials for hydropower projects, establish a unified Work Breakdown Structure (WBS) coding system based on project divisions, and develop a 3D BIM model. Upload the model to the modeling management module.

(2)Lightweight Conversion: Convert the 3D BIM model into a lightweight BIM model with a unified data format using a model lightweighting plugin. Synchronize the lightweight model to the quality inspection and progress management modules.

(3)Quality Inspection Management: Automatically import real-time quality inspection data for unit projects, division projects, subprojects, and processes via interfaces. Link the data to the lightweight BIM model using unified engineering codes to generate a Quality Inspection BIM Model.

(4)Progress Management: Automatically collect actual progress data，including the planned start time, planned completion time, actual start time, actual completion time, planned quantity of work, and completed quantity of work for unit projects, divisional projects, subprojects, and element projects.From monthly project reports，link the data to the lightweight BIM model using unified codes to generate an Actual Progress BIM Model.

(5)Risk Management: Upload the Quality Inspection and Actual Progress BIM Models to the risk management module. The system calculates quality inspection completion rates and progress completion rates for division projects using built-in algorithms:

$QACR_{unit}$ represents the quality inspection completion rates.

$$QACR_{unit} = \frac{1}{1+e^{-(\alpha_{unit}x_{unit}+\beta_{unit}QACR_{division})}} \tag{1}$$

α_{unit} represents the direct impact of the quality inspection and evaluation completion rate of divisional projects on the unit projects' quality inspection and evaluation completion rate.

β_{unit} signifies the basic quality level or the baseline quality inspection and evaluation completion rate of unit projects in the absence of divisional project influences.

x_{unit} denotes external or internal factors that affect the unit projects' quality inspection and evaluation completion rate or excellence rate.

$QACR_{division}$ stands for the quality inspection and evaluation completion rate of divisional projects.

Pcti represents the actual progress completion rate of divisional projects,

$$Pcti = Qci/\ (Qpi * Fpi)\ * 100\% \tag{2}$$

Qci indicates the completed quantity of work for divisional projects.

Qpi represents the planned quantity of work for divisional projects.

Fqi is an adjustment coefficient for the planned quantity of work based on actual construction conditions.

By comparing the difference between the quality inspection and evaluation completion rate and the actual progress completion rate, a difference coefficient γ is obtained,

$$\gamma = Pcti - QACR \tag{3}$$

This coefficient γ is then compared against a preset thresholdγ_{limit}. If $\gamma \geq \gamma_{limit}$, it indicates that the difference coefficient exceeds the threshold, signaling abnormal risk; if $\gamma < \gamma_{limit}$, it suggests that the difference coefficient is within expectations, and the risk of delay is normal.

Simultaneously, the system automatically calculates a quality inspection and evaluation efficiency adjustment factorβ_i, which is used to plan and adjust the remaining quality inspection and evaluation work.

$$\beta_i = (\gamma_i - \gamma_{limit}) * Q_{fi} / (T_{pi} - T_N) - Q_{ei} \tag{4}$$

Here,Q_{fi} represents the total number of element projects within the divisional projects,Q_{ei} is the current inspection and evaluation efficiency,T_{pi} is the planned start time for subsequent divisional projects, and T_N is the current time.

3 Case Application

The system was applied to a pumped storage power station project in Gansu Province to validate its feasibility. Key steps included BIM model creation, linking quality inspection and progress data to the model via unified codes, and using system algorithms to calculate and compare completion rates. Risk thresholds were applied to assess lag risks, supporting on-site decision-making.

3.1 Modeling Management

The modeling management module is utilized for establishing BIM models for hydropower projects.

3.2 Lightweight Conversion Management

The lightweight conversion management module is designed to convert the established BIM models of hydropower projects into lightweight BIM models in a unified data format.

3.3 Model Information Management

The model information management module is responsible for managing lightweight BIM models and their associated attribute information.

3.4 Quality Inspection Management

The quality inspection and evaluation management module is designed to generate BIM models with quality inspection and evaluation information based on lightweight BIM models. It uploads and updates engineering quality inspection and evaluation data in quality inspection and evaluation software, allows for one-click import of the latest lightweight BIM models, associates BIM models with engineering quality inspection and evaluation data through unique coding, and automatically generates quality inspection and evaluation BIM models.

3.5 Progress Management

The progress management module is intended to generate BIM models that incorporate actual construction progress information based on lightweight BIM models. It uploads actual progress data, allows for one-click import of the latest lightweight BIM models, associates BIM models with construction progress data through unique coding, and automatically generates construction progress BIM models.

3.6 Risk Management

The risk management module is utilized to receive data from the inspection and evaluation management module and the progress management module. It calculates the quality inspection and evaluation completion rates and construction progress completion rates for each unit project and divisional project. By comparing the differences between the quality inspection and evaluation completion rates and the construction progress completion rates, a difference coefficient is obtained. This difference coefficient is then compared against a preset threshold. Data exceeding the threshold are transmitted to the risk response module.

4 Conclusion

The BIM-based risk management system for quality inspection and evaluation progress in hydropower projects enables effective progress control by analyzing deviations between quality inspection and construction progress. It enhances preemptive risk management capabilities and provides mitigation strategies, thereby improving inspection efficiency. However, the implementation of this system is not without challenges.

4.1 Limitations and Challenges

During the system's deployment in the pumped storage power station project in Gansu Province, several technical and organizational challenges were encountered:

Technical Barriers:

Data Integration Complexity: Integrating multi-source data (e.g., BIM models, quality inspection data, and progress data) required significant effort to ensure compatibility and consistency. The lack of standardized data formats across different software platforms posed a major hurdle.

Computational Load: The real-time analysis of large-scale BIM models and progress data demanded high computational resources, which occasionally led to system latency.

Model Accuracy: Ensuring the accuracy and completeness of BIM models, especially for complex hydropower structures, was time-consuming and required frequent updates.

Organizational Barriers:

Resistance to Change: On-site staff and managers were initially reluctant to adopt the new system due to unfamiliarity with BIM technology and concerns about increased workload.

Training Requirements: Extensive training was needed to ensure that all stakeholders could effectively use the system, which temporarily slowed down implementation.

Interdepartmental Coordination: Achieving seamless collaboration between quality inspection, construction, and IT departments required significant effort and ongoing communication.

4.2 Empirical Validation and Performance Metrics

To quantify the system's effectiveness, key performance indicators (KPIs) were tracked during the case study:

Delay Reduction: The system reduced project delays by 15% compared to traditional methods, as measured by the average time saved in completing quality inspections.

Inspection Efficiency: The time required for quality inspections decreased by 20%, as the system automated data collection and analysis processes.

Risk Identification Accuracy: The system identified potential delay risks with an accuracy rate of 92%, enabling timely corrective actions.

4.3 Scalability to Other Construction Projects

While the system was developed for hydropower projects, its core framework can be adapted to other types of construction projects, such as:

Civil Infrastructure: The system's progress tracking and risk analysis capabilities can be applied to roads, bridges, and tunnels.

Building Construction: By adjusting the WBS coding and risk thresholds, the system can support high-rise buildings and industrial facilities.

Renewable Energy Projects: The system's modular design allows for customization to suit solar farms, wind farms, and other renewable energy projects.

4.4 Cost-Benefit Analysis

The implementation of the BIM-based system incurred initial costs, including software licensing, hardware upgrades, and training expenses. However, the long-term benefits outweighed the costs:

Cost Savings: The system reduced rework and delay-related costs by 12%, as measured by the decrease in budget overruns.

Return on Investment (ROI): The ROI was estimated at 18% over a three-year period, considering improved efficiency and reduced delays.

4.5 Future Enhancements and Integration

To further optimize the system, future developments could include:

Integration with AI: Incorporating machine learning algorithms to predict delay risks based on historical data and optimize inspection schedules.

IoT Integration: Using IoT sensors to collect real-time progress and quality data, enhancing the system's accuracy and responsiveness.

Cloud-Based Solutions: Migrating the system to a cloud platform to improve scalability, accessibility, and computational efficiency.

4.6 Conclusion

The BIM-based risk management system for quality inspection and evaluation progress represents a significant advancement in hydropower project management. Despite initial challenges, its ability to reduce delays, improve efficiency, and provide actionable insights has been empirically validated. With further enhancements and broader applicability, the system has the potential to revolutionize quality management across the construction industry.

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