Research on the Construction and Optimization Methods of Supervision Quality Evaluation Systems for Complex Engineering Projects

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Abstract： Complex engineering projects pose significant challenges to the control and evaluation of supervision quality due to their large scale, intricate systems, diverse stakeholders, and high technical complexity. Existing supervision quality evaluation systems exhibit limitations in indicator design, weight allocation, and dynamic feedback mechanisms, making it difficult to comprehensively reflect the actual performance of supervision work in complex projects. Based on this, this paper first analyzes the characteristics of complex engineering projects and their specific demands on supervision quality, identifying key issues in current evaluation systems. Subsequently, a supervision quality evaluation indicator system covering three dimensions—technical, managerial, and comprehensive—is constructed. A combined approach of the Analytic Hierarchy Process (AHP) and Entropy Weighting Method is introduced to determine comprehensive weights, enhancing the scientific rigor and objectivity of evaluation outcomes. Building upon this foundation, a comprehensive evaluation method for supervision quality is proposed, based on fuzzy comprehensive evaluation and an improved TOPSIS model, forming a relatively complete evaluation framework. Finally, the application pathways of information technology and big data in supervision quality evaluation and optimization are explored, and the feasibility and effectiveness of the constructed system are validated through case analysis. The study demonstrates that this system not only enhances the scientific rigor and systematic nature of supervision quality evaluation in complex engineering projects but also provides support for subsequent dynamic optimization and management decision-making.

1. Introduction

With the continuous advancement of infrastructure construction and large-scale engineering projects in China, the number and scale of complex engineering projects continue to grow[1]. Such projects typically feature long durations, substantial investments, multiple interdisciplinary aspects, and complex stakeholder involvement. This significantly increases uncertainties and risk factors during construction, substantially elevating the difficulty of quality control. As a critical safeguard for project quality, schedule, and investment control, the quality evaluation outcomes of engineering supervision directly impact the achievement of overall project objectives and the enhancement of project management standards[2].

Existing supervision quality evaluation systems predominantly rely on single-dimensional or experiential indicators, suffering from issues such as insufficient indicator coverage, highly subjective weight allocation, and a lack of dynamic and operational evaluation results[3]. These shortcomings are particularly pronounced in complex projects, potentially distorting supervision evaluations and undermining quality control and decision-support functions. Developing a scientific, systematic, and dynamically optimized supervision quality evaluation system has thus become critical for advancing complex project management[4].

Extensive research on supervision quality evaluation exists globally. Overseas studies pioneered multi-indicator comprehensive evaluation and fuzzy evaluation methods, emphasizing regulatory compliance and risk control capabilities in supervision work. Domestic research has focused on constructing and refining evaluation indicators, progressively incorporating methods such as the

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Analytic Hierarchy Process (AHP), entropy weighting, and grey relational analysis to enhance scientific rigor. However, practical application reveals persistent disconnects between evaluation systems and the actual demands of complex engineering projects, particularly regarding multidimensional assessment and dynamic optimization—areas where research remains insufficiently explored.

This paper will analyze the essence and requirements of supervision quality evaluation based on the characteristics of complex engineering projects, constructing an evaluation indicator system covering technical, managerial, and comprehensive dimensions. Methodologically, it will establish a scientifically sound indicator weighting system by integrating subjective and objective weighting approaches[5]. Regarding evaluation models, it will incorporate fuzzy comprehensive evaluation and an improved TOPSIS method to form a relatively comprehensive supervision quality evaluation framework. Leveraging information technology and big data, this study explores dynamic optimization pathways for the evaluation system and validates its feasibility and effectiveness through case studies[6]. The findings contribute to enhancing the scientific rigor and systematic approach of quality evaluation in complex engineering projects, providing valuable references for subsequent quality management and decision-making.

2. Analysis of the Essence and Requirements for Quality Evaluation in Complex Engineering Project Supervision

Complex engineering projects typically involve large scales, extended durations, multiple disciplines, and numerous contractors, characterized by high uncertainty and technical complexity. Such projects are prone to various risk factors during design, construction, and acceptance phases, including construction quality deviations, schedule delays, substandard materials, and environmental/safety issues[7]. Scientific and effective supervision quality management is crucial for ensuring smooth project implementation, controlling risks, and enhancing overall project quality[8]. To calculate the comprehensive score of supervision quality, the weighted sum of indicators can be used, as shown in Equation (1):

$$S = \sum_{i=1}^{n} w_i \cdot x_i \qquad (1)$$

Supervision quality encompasses not only the compliance of construction processes and the qualification of construction outcomes but also the comprehensive capabilities of supervision units in contract execution, construction organization management, risk control, and coordination/communication[9]. It reflects the supervision unit's mastery of engineering technology, management processes, and overall project objectives, serving as a key benchmark for evaluating the effectiveness of supervision work and project management standards[10]. The supervision quality scores of each project across technical, management, and comprehensive dimensions are shown in Figure 1. The heatmap provides an intuitive comparison of evaluation results among different projects:

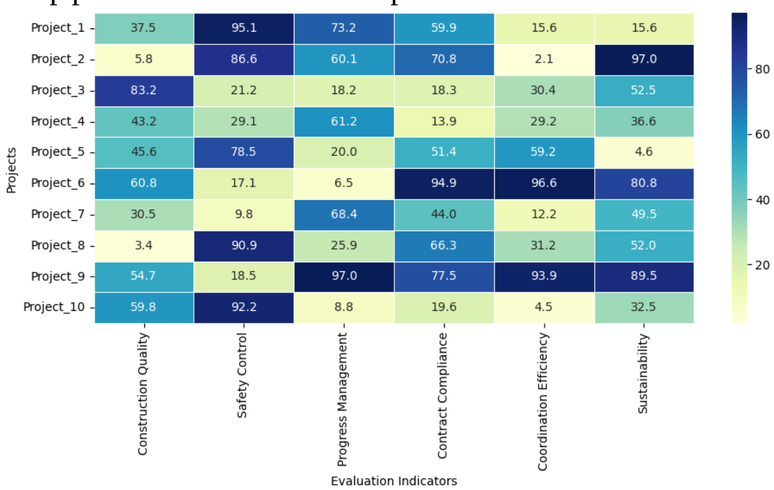

Figure 1 Technical, Management, Comprehensive Scores Heatmap

Currently, most supervision quality evaluation systems suffer from issues such as incomplete indicator coverage, highly subjective weighting allocations, and a lack of dynamic adjustment mechanisms. These shortcomings are particularly pronounced in complex engineering projects. Single or static evaluation methods struggle to fully reflect quality management during project implementation, often yielding results that diverge from actual supervision outcomes. This limits the system's value in quality control and decision optimization.

To address the characteristics of complex projects, the supervision quality evaluation system must be systematic, scientific, and dynamically adjustable. On one hand, it should encompass technical, managerial, and comprehensive dimensions to fully reflect the entirety of supervision work. On the other hand, it should incorporate reasonable weighting allocation and dynamic feedback mechanisms to enhance the objectivity and practicality of evaluation outcomes. Furthermore, integrating information technology and big data to enable real-time monitoring and optimization of project supervision quality, thereby supporting project decision-making, represents a crucial direction for meeting the quality control demands of complex engineering projects.

3. Construction of the Supervision Quality Evaluation System

To achieve scientific evaluation of supervision quality in complex engineering projects, this section will systematically construct a supervision quality evaluation system from a holistic perspective. First, by identifying key elements across technical, managerial, and comprehensive dimensions, a comprehensive and actionable evaluation indicator system will be designed to ensure coverage of all project implementation stages. Subsequently, scientific weighting methods will be introduced to determine the relative importance and practical impact of each indicator, enhancing the objectivity and reliability of evaluation outcomes. Finally, based on the designed indicator system and weighting information, a rational quality evaluation model will be constructed to enable quantitative analysis and comprehensive assessment of supervision work, providing theoretical and methodological support for subsequent optimization and decision-making.

3.1 Design of the Evaluation Indicator System

The design of the supervision quality evaluation indicator system should adhere to the principles of scientific rigor, systematic approach, operational feasibility, and quantifiability. Scientific rigor requires indicators to accurately reflect the core content and quality level of supervision work; systematic approach emphasizes that indicators should cover the entire construction process and all key stages; operational feasibility demands that indicators facilitate data collection and evaluation implementation; quantifiability ensures evaluation results can undergo quantitative analysis and comparison, providing a basis for subsequent optimization. To eliminate the dimensional differences among indicators, normalization is required, as expressed in Equation (2):

$$x_i{}' = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (2)$$

When determining the weights of indicators, the entropy method can be used to calculate the information and weight of each indicator, as shown in Equation (3):

$$e_j = -k\sum_{i=1}^{m} p_{ij} \ln p_{ij}, \quad k = \frac{1}{\ln m}$$

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \quad (3)$$

Technical Dimension Indicators primarily focus on the standardization of construction processes, construction quality, and technical management capabilities. These include the implementation of construction plans, control of critical processes, quality of materials and equipment, completeness of construction records, and the implementation of safety and environmental protection measures. Such indicators reflect the supervision unit's capabilities in engineering technical control and quality oversight, directly impacting the final quality of the project.

Management Dimension Indicators emphasize the evaluation of the supervision unit's capabilities in organizational coordination, contract management, progress control, risk management, and communication coordination. By monitoring and evaluating project management processes, the overall proficiency of the supervision unit in ensuring smooth project advancement, minimizing delays, and controlling cost overruns can be determined.

Comprehensive dimension indicators reflect the overall effectiveness and added value of supervision work, such as the level of information technology application, innovative management measures, environmental protection and sustainability considerations, and stakeholder satisfaction. These indicators facilitate a macro-level assessment of the supervision unit's contribution to the project's overall objectives, effectively complementing technical and management evaluations.

3.2 Method for Determining Indicator Weights

In the supervision quality evaluation system, the rational allocation of indicator weights directly impacts the scientific rigor and objectivity of evaluation outcomes. Different indicators exert varying degrees of influence on overall supervision quality. Therefore, scientific methods must be employed to assign appropriate weights to each indicator, reflecting their relative importance and preventing evaluation results from being distorted by subjective bias or omitted indicators.

Subjective weighting methods typically rely on expert judgment and empirical analysis, with the Analytic Hierarchy Process (AHP) being the most widely applied tool. By constructing an indicator hierarchy, performing pairwise comparisons, and calculating consistency ratios, expert opinions can be quantified into weights for each indicator. This method effectively leverages professional expertise but remains susceptible to subjective biases among experts. Based on the fuzzy comprehensive evaluation method, qualitative assessments of indicators can be converted into quantitative results, as presented in Equation (4):

$$B = A \cdot R \quad (4)$$

Objective weighting methods rely on actual data characteristics, such as entropy weighting and standard deviation weighting. The entropy weight method reflects an indicator's discriminative capability through its information content—greater information content yields higher weight—thereby ensuring evaluation objectivity. While objective weighting methods reduce human interference, they may overlook the importance of practical management experience.

To balance scientific rigor and practicality, a comprehensive weighting strategy combining subjective and objective approaches can be adopted. This involves integrating methods like AHP and entropy weighting through weighted fusion to derive final indicator weights. This approach fully considers expert experience while leveraging data objectivity, enhancing the accuracy and operability of the evaluation system and providing a reliable foundation for subsequent quality evaluation model construction.

3.3 Quality Evaluation Model Construction

The construction of a quality evaluation model aims to transform the evaluation indicator system and weight information into quantifiable, comparable comprehensive evaluation results, enabling scientific assessment of the supervision quality of complex engineering projects. Model design should adhere to principles of systematicity, operability, accuracy, and dynamic adjustability to ensure evaluation outcomes reflect actual supervision conditions while facilitating optimization and decision support. Using the improved TOPSIS method, the relative closeness of each project’s supervision quality can be calculated, as indicated in Equation (5):

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-} \quad (5)$$

Fuzzy comprehensive evaluation methods effectively address indicator ambiguity and uncertainty in supervision quality assessments. By establishing membership functions to convert qualitative indicators into quantitative evaluations, combined with fuzzy comprehensive calculations incorporating indicator weights, a comprehensive supervision quality score can be obtained. This method is suitable for multi-dimensional, multi-level evaluation systems and effectively reflects the overall quality level of supervision in complex engineering projects. The comparison of different projects across technical, management, and comprehensive dimensions is illustrated in Figure 2. The radar chart clearly shows the differences among projects in multi-dimensional indicators:

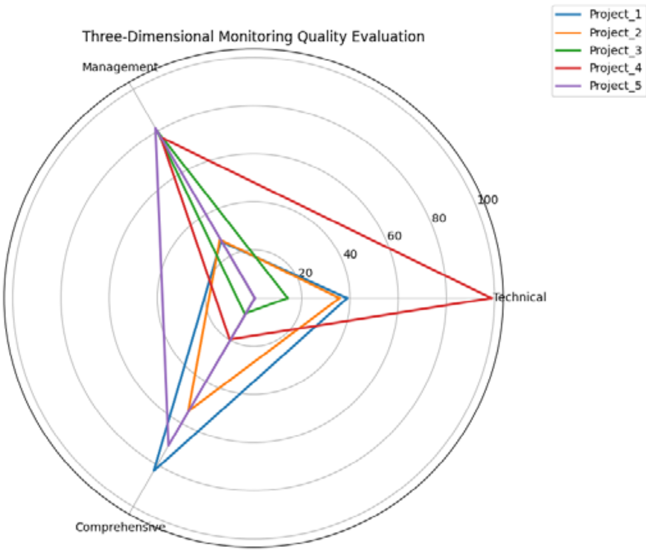

Figure 2 Radar Chart of Three-Dimensional Evaluation

The improved TOPSIS model ranks evaluation results for each project supervision unit by constructing ideal and negative ideal solutions, enabling comprehensive comparative analysis of relative strengths and weaknesses. Introducing weight adjustments and fuzzy processing into the model enhances sensitivity to variations among various indicators in complex engineering projects, yielding more scientific and reasonable evaluation outcomes.

Based on the aforementioned model, the supervision quality evaluation process encompasses indicator data collection, indicator standardization, weight assignment, composite score calculation, and result analysis/ranking. Evaluation outcomes provide project managers with intuitive, quantifiable references to guide supervision work improvements and optimization. Furthermore, integrating information platforms and big data technologies enables dynamic updates and optimization of the evaluation model, enhancing the real-time responsiveness and sustainability of supervision quality management in complex engineering projects.

4. Optimization and Application of the Supervision Quality Evaluation System

Complex engineering projects typically involve multiple disciplines, contractors, and extended timelines, with uncertainties in technology, management, environment, and safety throughout implementation. This makes it challenging for static supervision quality evaluation systems to comprehensively reflect actual project conditions. Furthermore, as construction techniques and management methods evolve, traditional evaluation systems often suffer from outdated indicators, unreasonable weightings, and distorted results. Therefore, establishing a sustainable optimization mechanism that adapts to project progress and external environmental changes while effectively enhancing the scientific rigor, standardization, and systematic nature of supervision work is a crucial prerequisite for achieving high-quality engineering construction. To realize the dynamic optimization of the evaluation system, the weights of indicators can be adjusted, as described in Equation (6):

$$w_i^{(t+1)} = w_i^{(t)} + \alpha \cdot \Delta S_i \qquad (6)$$

The optimized evaluation system should incorporate a comprehensive dynamic feedback mechanism. By continuously collecting and analyzing various data generated during the supervision process (such as construction quality records, progress monitoring information, risk event statistics, and acceptance results), it should generate periodic or real-time evaluation feedback. This feedback mechanism not only facilitates adjustments to evaluation metrics and weightings but also identifies weaknesses in the supervision process, providing targeted improvement recommendations for managers. For instance, if evaluation results indicate low scores for a critical process, the frequency of on-site inspections can be promptly increased or the supervision plan optimized to achieve closed-loop management. The dynamic feedback mechanism can also be integrated with project milestone phases to enable phased evaluation and optimization, making the evaluation system more flexible and responsive to practical needs.

With advancements in information and intelligent technologies, optimizing supervision quality evaluation can leverage big data analytics, data mining, and visualization techniques to enhance efficiency and accuracy. By establishing a supervision data platform that aggregates construction logs, supervision records, quality inspection data, and safety audit data, comprehensive cross-project and cross-disciplinary analysis becomes achievable. Applying machine learning algorithms and predictive models can identify potential risks, analyze quality trends, and generate optimization recommendations. Visualization technology intuitively presents supervision quality metrics alongside project progress, costs, and risk status, providing data-driven support for decision-makers. Concurrently, information technology enables automation and intelligence in the evaluation process, reducing manual intervention while enhancing the system's real-time responsiveness and reliability.

In practical project implementation, the optimized supervision quality evaluation system delivers quantifiable and actionable decision-making references for project management. For instance, in a large-scale complex project, the indicator system quantitatively assessed scores across supervision phases. Combined with a dynamic feedback mechanism, it identified deficiencies in construction coordination and IT application. Subsequently, management adjusted supervision plans and resource allocation, monitoring improvement outcomes through big data analysis. Results demonstrated that these optimization measures effectively elevated quality scores for critical processes while improving overall project progress and management efficiency. This not only validated the scientific rigor and feasibility of the evaluation system but also provided valuable experience and methodological references for quality management in subsequent similar projects.

Moving forward, the optimization of the supervision quality evaluation system will further integrate technologies such as artificial intelligence, BIM (Building Information Modeling), and digital twins to achieve higher levels of intelligent and visual management. By introducing predictive analytics and intelligent early warning mechanisms, potential quality risks can be forecasted during the pre-construction phase, enabling dynamic adjustments to supervision strategies throughout the construction process. Furthermore, integration with cloud computing platforms facilitates cross-project and cross-regional sharing and comparative analysis of supervision data, promoting industry standardization and the formation of best practices. This ultimately elevates the overall management level and construction quality of complex engineering projects.

5. Conclusion

This paper systematically constructs a scientific, comprehensive, and optimizable supervision quality evaluation system for complex engineering projects, proposing optimization methods and application strategies. Due to their large scale, multidisciplinary nature, extended timelines, and technical complexity, complex projects impose heightened demands on supervision. By analyzing project characteristics and existing evaluation system limitations, this study establishes the necessity for a scientific supervision quality framework, providing theoretical foundations and practical context.

The paper proposes an evaluation indicator system covering three dimensions—technical, managerial, and comprehensive—ensuring the assessment encompasses the entire construction process and core supervision functions. For determining indicator weights, a combined approach of subjective and objective weighting enhances the scientific rigor and objectivity of weight allocation. Based on this, the constructed fuzzy comprehensive evaluation and improved TOPSIS model achieve quantitative evaluation and comprehensive ranking of supervision quality, providing engineering managers with an actionable decision-making tool. To address the dynamic adaptability of the evaluation system in practical applications, this paper proposes optimization strategies including a dynamic feedback mechanism, the application of information technology and big data, and validation through practical case studies. The optimized system enables real-time monitoring of supervision quality, identifies issues, and provides improvement measures, achieving closed-loop management. This effectively enhances the quality management level and decision-support capabilities for complex engineering projects.

The supervision quality evaluation system will further integrate technologies such as artificial intelligence, BIM, digital twins, and cloud computing to achieve intelligent, visual, and cross-project comprehensive evaluation. By incorporating predictive analytics and intelligent early warning mechanisms, it can anticipate potential risks during the early construction phase and dynamically adjust supervision strategies, providing continuous support for high-quality construction of complex engineering projects. This research provides a theoretical foundation and practical reference for subsequent standardization of supervision evaluation systems, method optimization, and application promotion. The constructed supervision quality evaluation system and its optimization methods not only enrich the theoretical framework for managing complex engineering projects but also provide scientific tools and operational pathways for project management practice. This holds significant importance for enhancing the construction quality of complex engineering projects in China.

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