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

Xianglin Du

Anhui Tianhan Engineering Consulting Co., Ltd., Ma'anshan, Anhui, 243000, China

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Abstract: The large scale, complex systems, collaboration of multiple stakeholders, strong technical complexity, etc. of engineering projects make it difficult to control and evaluate the quality of supervision on these projects. The current quality evaluation systems of existing supervision work, that is indicator design, weight assignment and dynamic feedback mechanism are relatively limited, which makes it difficult to reflect the actual state of supervision work in complex projects. To this end, this paper first analyzes the relevant characteristics of complex engineering projects and their specific requirements for supervisor quality as well as problems existing in the current evaluation system. Then, a supervision quality assessment indicator system under three dimensions (technical dimension, manager aspect dimension and comprehensive dimension) is established. A method that combines Analytic Hierarchy Process (AHP) with Entropy Weighting Method is proposed to obtain comprehensive weight, thus improving the scientificity and objectivity of evaluation result. On top of this foundation, a comprehensive evaluation method measuring the supervision quality is constructed based on fuzzy comprehensive evaluation and improved TOPSIS model to obtain a relatively complete evaluation framework. Next, the potential application paths of information technology and big data in supervision quality evaluation and optimization are discussed, together with case analysis validating the feasibility and economic effectiveness of constructed system. This study indicates that the suggested model can not only improve the rigorousness and systematicness of evaluation for supervision quality, but also contribute to further dynamic optimizing and managing decision-making in complex engineering projects.

1. Introduction

As the infrastructure construction and large-scale engineering projects in China continue to develop, the number and scale of complex engineering projects present new characteristics [1]. These projects often have long time horizons, large budgets, multi-disciplinary components and complex impacts across multiple stakeholders. Such creates tremendous uncertainties and risk factors in the construction for quality control, which greatly increases the difficulty of supervision. Principally used in construction, the quality evaluation outcomes of engineering supervision are a critical safeguard for project quality, project schedule control and return on investment that directly influence the achievement of overall project objectives as well as improvement of the project management level [2].

Current systems for assessing the quality of supervision rely mostly on uni-dimensional and experience-based indicators, which have problems such as low indicator coverage rate, high subjectivity in weight allocation, and poor dynamic and operational evaluation results [3]. These shortcomings become especially pronounced in complex projects where supervision evaluations can be distorted, and quality control and decision-support functions compromised. It is thus essential to establish a scientific, systematic, and dynamic optimization of supervision quality evaluation system for improving complex project management [4].

There are several studies about the quality of supervision evaluation around the world. Abroad work, took the lead in multi-index comprehensive evaluation and fuzzy evaluation method to the supervision work, highlights the regulatory compliance degree and risk control ability. By integrating AHP, entropy weighting, and grey relational analysis methods, scientific research on domestic evaluation indicators has transitioned from building towards continuous exploration. Yet, implementation demonstrates ongoing disconnects between evaluative systems and what complex engineering projects require in practice; these diverging aspects include multidimensional assessment input-output relationships and dynamic optimization—a realm yet to be well researched.

Based on the characteristics of complex engineering projects, this paper analyzes the nature and requirements of supervision quality evaluation, establishes an evaluation indicator system covering technical dimension, managerial dimension and comprehensive dimension. From the methodological perspective, it will create a scientifically robust indicator weighting system by merging the subjective and objective weighting methods [5]. In terms of evaluation models, it will integrate the fuzzy comprehensive evaluation method and an optimized TOPSIS method to establish a relatively all-round supervision quality evaluation framework. Using information technology and big data, this study identifies dynamic optimization methods for the evaluation system, and verifies the feasibility and effectiveness of the optimization method through case studies [6]. These findings can enhance the scientific rigor and systematic nature of quality evaluation in complex engineering projects, allowing for valuable references to future quality management and decision-making.

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

Large-scale, complex projects in engineering are by nature long-term, multi-disciplinary and they also have many contractors with unique management structures that underlie high uncertainty and technical complexity. Projects like these are threatened with risks from design, construction and acceptance stages such as deviations from quality standards of the work, delays in schedule, poor-quality materials and environmental/safety-related issues [7]. The quality management of supervision at this stage is a scientific and effective measure to ensure the timely, smooth, and efficient implementation of engineering projects, control various risks in the project construction process, and improve the overall quality of projects. By implementing it [8]. To calculate the comprehensive score of supervision quality, the weighted sum of indicators can be used, as shown in Equation (1):

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

Quality of supervision refers to the compliance of construction processes and qualification of construction outcomes, as well as the capacity of comprehensive abilities for supervisory units in contract execution, construction organization management and risk control, coordination/communication [9]. It also represents the supervision unit's proficiency in engineering technology, management processes and general project objectives; it is an essential standard to evaluate the effectiveness of supervision work and the level of project management performance [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:

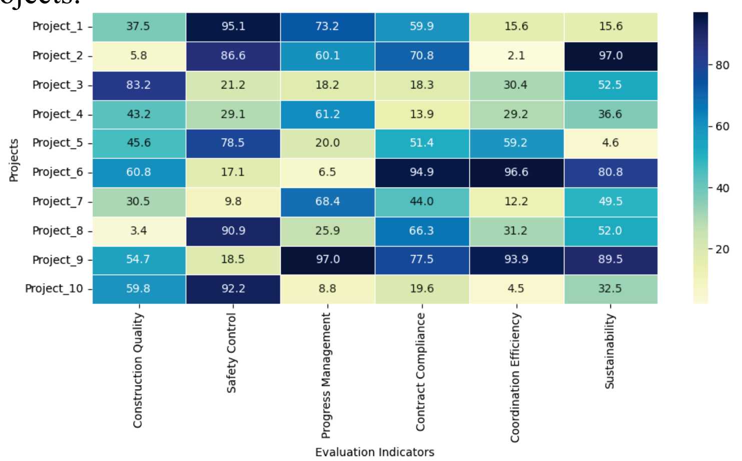

Figure 1 Technical, Management, Comprehensive Scores Heatmap

Most of the supervision quality evaluation systems at present encounter problems, including incomplete indicator coverage,highly subjective weighting allocation and loss of dynamic adjustment mechanism on weight. These weaknesses are particularly acute in complex engineering projects. Static or single periodic evaluation types do not completely guide on implementation of the quality management system in project performance as during supervision due to their results deviate from actual supervision results. This restricts the value of the system in quality control and decision optimization.

As complex projects have characteristic qualities, the supervision quality evaluation system should be systematic and scientific with dynamic adjustability. It is important because on the one hand it should also cover technical, managerial and comprehensive aspects to represent the whole picture of supervision work. However, it must include a reasonable weighting allocation and dynamic feedback systems to improve evaluation results in terms of objective fairness and practical implications. In addition, the integration of information technology and big data to conduct real-time monitoring and optimization on project supervision quality based on project decision-making has become an important way to meet the quality control requirements of complex engineering projects.

3. Construction of the Supervision Quality Evaluation System

In order to evaluate the quality of supervision through scientific methods in complex engineering projects, this section will systematically create a set of evaluation system for supervision quality from the perspective of entire system. 1) covering all implementation stages through creation of a comprehensive and actionable evaluation indicator system, by identifying key elements across technical, managerial and comprehensive dimensions. Then scientific weighting methods will be added to objectively weigh the importance and practical significance of each indicator and enhance the objectivity and reliability of evaluation results. In the end, a reasonable quality evaluation model will be constructed on the basis of design indicators system and weighting information, which can realize quantification analysis and comprehensive evaluation for supervision works, so as to provide theoretical and methodological support for subsequent optimization decision-making.

3.1 Design of the Evaluation Indicator System

Design principles for the supervision quality evaluation index of indicators, including scientific rigor; systematic; operability and quantifiability. It is scientifically rigorous to make indicators reflect the core elements and quality level of supervision work; systematic approach requires these indicators cover the whole construction process, covering all key points; logistical feasibility requires that such indicators can facilitate data collection and evaluation implementation during practical application; quantifiable guarantees require that subjects are able to be quantified for analysis selection and comparison so as to provide 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 are mainly aimed at the standardization of construction processes, construction quality and technical management capabilities. Such factors may include execution of construction plans, control of critical processes, quality of materials and equipment, completeness of construction records as well as implementation of measures on safety and environmental protection.

These indicators outline the abilities of the supervising team in terms of design technical control and quality control, thereby influencing the ultimate quality outcome of the project.

Management Dimension Indicators focus on evaluating the supervision unit's capabilities in organizational coordination, contract management, progress control, risk management and communication coordination. For this, evaluating and continuously monitoring the project management processes demonstrates the overall competence of the supervision unit in smooth progress of a project, mitigation of time overrun and relieving from cost overrun.

These comprehensive dimension indicators embody the overall effectiveness and significance of supervision work: the permeation degree of information technology application, management innovative methods pursued, environmental protection and sustainable development's value pursuit, and stakeholder satisfaction index. It simplifies the macro-evaluation of supervision unit's contribution to achieve overall objectives, thus supplementing technical and management evaluations.

3.2 Method for Determining Indicator Weights

Indicator weight allocation plays a key role in the scientific rigor and objectivity of evaluation results generated during the academic supervision quality evaluation system. Different indicators have different weighted impacts on overall supervision quality. Hence it is necessary to use scientific methods to assign appropriate weights for each indicator, so that the evaluation results will not be biased by subjective bias or missing indicators.

Subjective weighting approaches mostly depend on the expert assessment and empirical analysis of weights, where Analytic Hierarchy Process (AHP) is the most common employed technique. Through creating an indicator hierarchy, conducting pairwise comparisons and calculating consistency ratios, weights for each indicator can be assessed from expert opinions. This approach effectively harnesses professional expertise, but it is also susceptible to expert biases. Based on the fuzzy comprehensive evaluation method, qualitative assessments of indicators can be converted into quantitative results, as presented in Equation (4):

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

These approaches use the actual data characteristics, for instance, entropy weighting and standard deviation weighting as objective weighing methods. Based on the information content of an indicator, the entropy weight method reflects its distinguishing ability, so it gives a larger weight to indicators with higher information content in order to guarantee evaluation objectivity. Though objective methods of weighting reduce the human element, they can also miss out on practical experience managing these issues.

The balance between rigor and practicality can be achieved employing a weighting strategy that incorporates both subjective and objective approaches. The final weights of each index are obtained by fusing weights through weighted fusion, and integrated the methods like AHP and entropy weighting. This method not only accounts for the professional experience of experts, but also takes advantage of the objectivity of data to improve the accuracy and ability to operate on production unit evaluation system, laying a reliable foundation for building subsequent quality evaluation model.

3.3 Quality Evaluation Model Construction

The purpose for constructing a comprehensive evaluation model is to establish quantizing and comparability of the evaluation index system, weight information as well as integrate them into generalized comprehensive evaluation results so that we can assess scientifically on supervision quality of complex engineering projects. To achieve evaluation results that accurately represent actual supervision conditions as well as optimize models and support decision-making, model design must be carried out according to systematicity, operability, accuracy and dynamic adjustability. Using the improved TOPSIS method, the relative closeness of each project's supervision quality can be calculated, as indicated in Equation (5):

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

The fuzzy comprehensive evaluation method is an effective approach to solving the ambiguity and uncertainty of indicators in supervised quality evaluation. This is done by setting membership functions to transform qualitative indicators into quantitative evaluations and applying fuzzy comprehensive calculations with indicator weights to derive a comprehensive supervision quality score. This is an approach for multi-dimensional and multi-level assessment system, which shall objectively reflect the overall quality of supervision level in complex counterpart project.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:

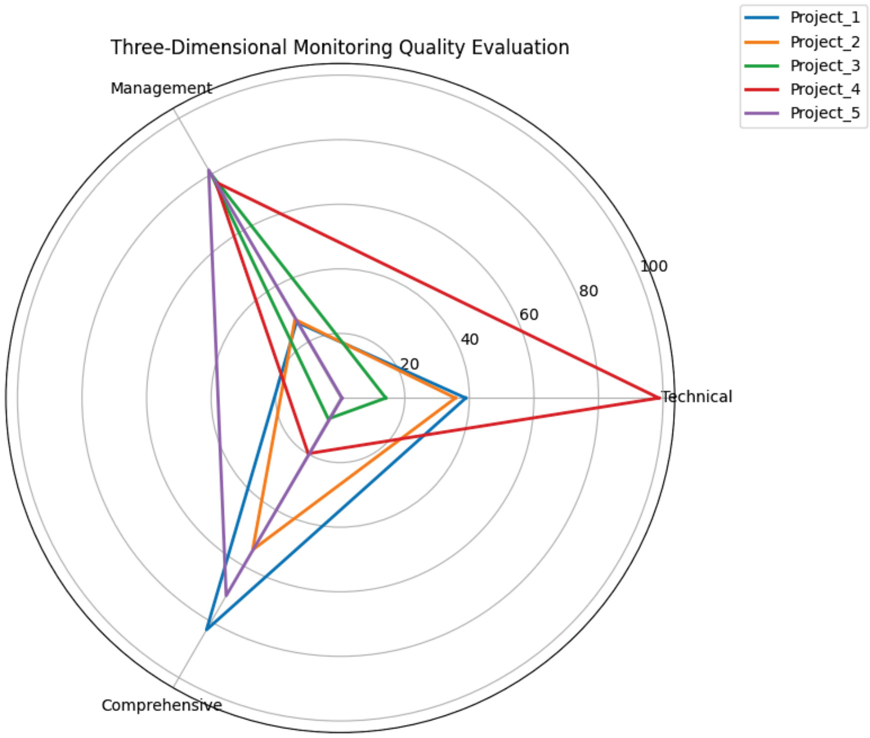

Figure 2 Radar Chart of Three-Dimensional Evaluation

By constructing ideal and negative ideal solutions, the improved TOPSIS model gives evaluation results and ranks for each project supervision unit so that relative advantages of weaknesses within the same category can be analysed comprehensively. Implementing weight or fuzzy processing into the model improves sensitivity for differences among multiple indicators in complex engineering projects, resulting in more scientific and reasonable evaluation results.

As a result of the above model, the process of evaluating supervision quality includes indicators data collection, indicator standardization, weight assignment, composite score calculation and results analysis/ranking. Using the quantifiable evaluation outcomes, project managers can make informed adjustments to the supervision process. Moreover, the combination of information platform and big data technology allows for dynamic updating and optimization of the evaluation model, improving real-time response ability as well as sustainability management quality of supervision in complex engineering projects.

4. Optimization and Application of the Supervision Quality Evaluation System

This is due to the fact that complex engineering projects typically encompass a variety of disciplines, contractors, and timeframes as well as uncertainties surrounding technology, management, environment and safety during implementation. This presents a difficulty for static supervision quality evaluation systems in deeply reflecting the actual situation of projects. What's more, with the developments of building crafts and management maanners, traditional evaluations systems often have out-of-date indications, unreasonable weight distributions and distorted results. Based on the above analysis, it is a prerequisite for high-quality engineering construction to establish an effective and sustainable optimization mechanism in supervision of engineering project adapts to the change of project phase and external environment while effectively enhancing scientific rigor, standardization and systematicness of supervision work. To realize the dynamic optimization of the evaluation system, the weights of indicators can be adjusted, as described in Equation (6):

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

An enhanced evaluation system with a dynamic feedback mechanism. It is supposed to produce periodic evaluation feedback or real-time evaluation feedback by constantly collecting and analyzing various data in the process of supervision (including construction quality records, progress monitoring information, risk event statistics, acceptance results, etc.). This feedback system helps not only to review and adjust from time to time the measures and weights used in evaluation but also to identify gaps in supervision (macro)/(micro) process and what managers can do specifically for improvement. For example, if the evaluation results show that critical processes score continuously lower than certain value, then the frequency of onsite inspections can be increased immediately or supervision plan optimized to achieve closed-loop management. Moreover, dynamic feedback can also be linked to project milestone phases, allowing for phased evaluation and optimization of the evaluation system and making it more flexible and responsive to real-world needs.

The improvement of the quality evaluation on supervision can make full use of big data analysis, data mining and visualization technology to enhance the efficiency and accuracy in this field under the support of information and intelligent technologies. (3) By building a supervision data platform where construction log, supervision record, quality inspection and safety audit data are collected and stored in a unified manner, all-round cross-project and cross-discipline analysis can be realized. Machine learning algorithms and predictive models can be applied to identify potential risks, analyze quality trends, and build optimization recommendations. Intuitive visualization technologies show supervision quality metrics right next to project progress, costs, and risk status allowing data-driven support for decision-makers. At the same time, information technology provides tools for automating and intelligent processing of evaluation, decreasing manual input but increasing system real-time response and reliability.

Practically, the optimized supervision quality evaluation system provides a basin for quantifiable and practical decision-making suggestions for project management. For example, quantifying scores in supervision phases for a huge scale complex project. In combination with this dynamic feedback mechanism, it used questionnaire results to find deficiencies in construction coordination and IT application. Management then modified supervision plans and resource allocation, using big data analysis to track improvement outcomes. The results indicate that these optimization methods helped to apply increased quality, for leading business processes and significantly development in project management. This not only demonstrated the scientific rigor and feasibility of the further evaluation system but also accumulated experience and methodology reference for quality management of similar projects in the future.

In the future, the supervision quality evaluation system will be continuously optimized and integrated with a variety of technologies (such as artificial intelligence, BIM digital twins) to realize management goals at a higher level of intelligence and visualization. Predictive analytics and intelligent early warning mechanisms forecast potential quality risks during the pre-construction stage, dynamically adjusting supervision strategies in time throughout the construction process. Moreover, the integration of supervision data with cloud computing platforms is conducive to cross-project and regional sharing and comparative analysis of supervision data, thereby promoting industry standardization and the formation of best practices. This ultimately improves the overall level of management and construction quality for complex engineering projects.

5. Conclusion

This paper systematically establishes a scientific, comprehensive and optimizable supervision quality evaluation system of complex engineering projects, as well expounds optimization methods and application strategies. Complex projects with larger scale, multi-discipline detail work efforts, long-duration schedules and technological complexity put much greater demands on the supervision. Then, through the analysis of project characteristics and existing evaluation system deficiencies, this study constructs the need for a scientific quality supervision framework, so as to give theoretical basis and practical background.

To ensure that the evaluation is relatively comprehensive, including the entire construction process as well as core supervision functions, three dimensions (technical dimension, managerial dimension and comprehensive dimension) of an evaluation indicator system are proposed in this paper. Weight allocation can be guided with both subjective and objective weighting, thus improving the scientific rigor and objectivity of indicator weights. In perspective of this, a quantitative evaluation and comprehensive ranking for supervision quality has been realized through the constructed fuzzy comprehensive evaluation and improved TOPSIS model, which provides engineering managers with practical decision-making reference. In summary, to solve the adaptability problem of evaluation system used in practice dynamically, this paper puts forward some optimization methods such as dynamic feedback mechanism, information technology and big-data technology application method and practical case study verification. Real-time monitoring supervision quality, problem identification prompt and improvement measures to form a closed loop management. This substantially improves the level of quality management and decision-support capabilities of complex engineering projects.

The whole quality supervision evaluation system, based on artificial intelligence technology, the project integrity evaluation model (BIM), digital twins and cloud computing will be integrated to achieve intelligent, visual and cross project comprehensive evaluation. It uses predictive analytics and smart early warning mechanisms to identify potential risks in the initial stage of construction, dynamically adjust supervision strategies, and continuously provide support for high-quality complex engineering project construction. The quality evaluation system and its optimization methods for constructive supervision created in this study not only enriches the theoretical research framework of complex engineering project management, but also are of significant guiding significance to the scientific tools and operational paths of project management practice. This is crucial to improve the construction quality of complex engineering projects in China.

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