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A NOVEL EVALUATION MODEL FOR SUBCONTRACTOR PERFORMANCE IN THE CONSTRUCTION INDUSTRY BASED ON FUZZY BORDA METHOD

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Abstract. The evaluation results obtained from different evaluation methods exhibit significant variations, which present a challenge to the traditional multi-attribute evaluation problem in subcontractor evaluation within the field of architectural engineering. To address this issue, this study proposes a novel evaluation model for subcontractor evaluation in architectural engineering, which is based on the fuzzy Borda method. Firstly, an evaluation index system for subcontractors in architectural engineering is established. Subsequently, an evaluation model is constructed using the fuzzy Borda method, which combines multiple evaluation results from various perspectives. This model overcomes the limitations and disparities inherent to individual evaluation methods and yields more accurate evaluation outcomes. To illustrate the effectiveness of the proposed model, a case analysis is performed based on the evaluation of subcontractors specializing in deep foundation pit engineering for the Dayuecheng project in Nanchang, China. The findings demonstrate that the results derived from the proposed model are more consistent with reality in comparison to other classic evaluation methods. Furthermore, this study quantitatively examines the consistency between the combined evaluation results obtained using the fuzzy Borda method and the evaluation outcomes from multiple evaluation methods, along with providing recommended threshold values.

1. Introduction

As one of the most common modes of project management, the general contracting model has been widely used in various construction fields due to its advantages of reducing construction costs, controlling project costs, and improving project performance. In this model, subcontractors have a significant influence on the implementation progress, cost, and quality of construction projects [9]. Since the evaluation of specialized subcontractors in the construction industry involves multiple factors, the decision-making process is complex and represents a typical multi-attribute evaluation problem. Therefore, how to scientifically and accurately evaluate specialized subcontractors, to provide a scientific basis for general contracting management in construction projects, holds significant scientific and engineering value.

The primary evaluation method currently used in the field of architectural engineering for subcontractors is the comprehensive evaluation method. This method

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assesses subcontractors' professional capabilities by considering their business capacity and technical capacity and utilizes the comprehensive index method to determine the final results. Various research methods, including the fuzzy comprehensive method (FCM) [5], matter-element analysis (MEA) [12], grey analysis (GA) [13], and set pair analysis (SPA) [14], were commonly employed for multi-attribute evaluation problems. However, these evaluation methods differed in their calculation principles, leading to inconsistent research findings when applied to subcontractor evaluation in the construction engineering profession. As a result, this inconsistency posed challenges for managers in accurately determining the true capabilities of subcontractors and hampered the effectiveness of subcontractor evaluation. Additionally, these research methods had varying scopes of applicability, further complicating the situation. Thus, the limitations of using a single evaluation method and the variability of multiple evaluation results emerged as significant challenges in this research field.

Currently, an increasing number of scholars are seeking to integrate the results of multiple evaluation methods to obtain a comprehensive evaluation result. This approach not only enables the utilization of more information, but also addresses the limitations of individual evaluations, resulting in a complementary effect. The fuzzy Borda method is an innovative and comprehensive evaluation method that integrates diverse results from various evaluation methods, thereby improving the reasonability and superiority of the evaluation outcomes. For instance, He et al. [6] applied the fuzzy Borda method to combine the results of four evaluation methods, and their research demonstrated that the combined evaluation results were more closely aligned with the actual case. Additionally, Ma and Zhang [8] effectively dealt with the issue of multidimensionality in power grid state assessment by employing the fuzzy Borda method. Moreover, Li and He [7] devised a binary semantic Borda method, which effectively addressed uncertainties in evaluating hospital service quality. Zhu et al. [17] conducted a comprehensive evaluation of tomato fruit quality using four single comprehensive evaluation methods and used the fuzzy Borad method to determine the drip irrigation strategy for tomatoes. Du and Gao [3] evaluated the risks and benefits of PPP projects based on the fuzzy Borda method and determined the decision mechanisms for investment risk sharing, incentives, and regulatory penalties in PPP projects. However, these research efforts did not quantitatively assess the consistency between the combined evaluation results based on the fuzzy Borda method and the evaluation results obtained from various evaluation methods.

To address this issue, this paper introduced a novel evaluation model for subcontractors in the field of architectural engineering, based on the fuzzy Borda method. The evaluation model was then applied to analyze the subcontractors involved in the deep foundation pit project of Dayuecheng in Nanchang, China. The potential contributions of this paper were summarized as follows: (1) The proposed model combined the research results of multiple evaluation methods using the fuzzy Borda method. This overcame the limitations and disparities of a single evaluation method and avoided contradictions in the results of multiple evaluation approaches. (2) By incorporating a case study, this paper discussed the rationality of using the golden section point as a threshold for determining whether to combine the results. The findings of this research provided valuable insights for the management of subcontractors in the field of architectural engineering.

2. Evaluation index system for subcontractors in the construction engineering major

The subcontracting of construction projects involves the process in which a general contracting unit for a construction project delegates specific portions or multiple parts of the project to other contracting units. These units then sign subcontract agreements with the general contractor under the main contract.

The evaluation index system refers to an organic whole with an internal hierarchical structure, composed of several indicators that represent the various characteristics of the evaluation object and are related to it. Building on an extensive review of the literature and considering the subcontractor selection process in practical projects, this paper establishes the primary indicators as business bids (X_1) and technical proposal (X_2). Business bids primarily indicate the subcontractors' economic capacity and reputation, while the technical proposal reflects their construction organization and management control abilities. Consequently, the evaluation index system for subcontractor selection in construction engineering is divided into three levels: the primary indicators include business bids and technical proposal, and the secondary indicators consist of economic capability, subcontractor reputation, construction organizational ability, and management control ability. Drawing from relevant research findings [1, 4, 11], seventeen specific indicators that reflect the secondary indicators are selected as tertiary indicators. Please see Table 1 for further details.

Table 1. Evaluation index system for selecting subcontractors in construction engineering

Primary index	Secondary index	Tertiary index	Type
X_1: Business bids	X_{11}: Economic capability	X_{111}: Total bid price	Quantitative
		X_{112}: Quotation for measures	Quantitative
		X_{113}: Flow ratio	Quantitative
		X_{114}: Debt-to-asset ratio	Quantitative
		X_{115}: Financing capability	Qualitative
	X_{12}: Subcontractor reputation	X_{121}: Winning bid rate	Quantitative
		X_{122}: Performance rate	Quantitative
		X_{123}: Industry evaluation	Qualitative
		X_{124}: Qualification level	Quantitative
X_2: Technical proposal	X_{21}: Construction organizational ability	X_{211}: Rationality of construction deployment	Qualitative
		X_{212}: Rationality of construction plan	Qualitative
		X_{213}: Equipment allocation of construction machinery	Qualitative
	X_{22}: Management control ability	X_{221}: Collaborative communication skills	Qualitative
		X_{222}: Quality management capabilities	Qualitative
		X_{223}: Safety and civilized construction management capabilities	Qualitative
		X_{224}: Schedule management capabilities	Qualitative
		X_{225}: Risk control capabilities	Qualitative

3. Combination method based on fuzzy Borda method

The Borda method determines the weights of each evaluation criterion through majority principles and ranking rules, which means that decision-makers can rank the criteria based on their subjective judgment and experience, thus enhancing their subjective involvement. At the same time, the Borda method avoids the inapplicability of certain algorithms to specific research problems and prevents significant biases in evaluation results when a single evaluation method is erroneous. The basic steps of the proposed combination method in this paper are as follows:

Step 1: Data collection and evaluation of single methods.

Based on the indicator system in Table 1, data related to the evaluation of subcontractors in the field of construction engineering was collected. Multiple multi-attribute evaluation methods were used to assess the subcontractors, resulting in evaluation results denoted as $\{x_{ij}\}$. Here, x_{ij} represented the score of the ith indicator obtained using the jth evaluation method, indicating the ability of the evaluation method to produce favorable evaluation results. Since different evaluation methods might have different comment sets, this paper transformed the evaluation results obtained from different methods into rankings. The ranking was used in subsequent verification processes, while the evaluation results were used in the combination calculations.

Step 2: Determine the need for combined evaluation.

Due to its wide applicability, intuitive results, and strong robustness, the Kendall coefficient of concordance had been widely used in the Borda method [2,6] . Therefore, this paper adopted the Kendall coefficient of concordance to test the closeness of single evaluation results:

$$K = \frac{12\sum_{i=1}^{n}(R_i - \overline{R}_i)^2}{(m+1)^2(N^3 - N)}, \tag{3.1}$$

where K is the consistency coefficient, m is the number of single evaluation methods, n is the number of indicators, and R_i is the sum of ranks for each sample point. The value range of K is [0,1], the closer the value is to 1, the stronger the correlation. When the correlation among multiple evaluation results is high, it indicates that the evaluations are consistent, and there is no need to use the fuzzy Borda method for reordering. A threshold value of 0.8 is suggested for K [10,16]. This means that when K is greater than or equal to 0.8, it can be considered that multiple evaluation results are consistent. If K is less than 0.8, it suggests that there are significant conflicts among the multiple evaluation results, and the fuzzy Borda method should be used to preprocess the evaluation results.

Step 3. Combination method for multiple evaluation results based on fuzzy Borda method.

(1) Due to the possibility of different evaluation comment sets for different evaluation methods, this study preprocesses the evaluation results $\{x_{ij}\}$ obtained from multiple methods [6]:

$$x_{ij}^* = \frac{x_{ij} - \min\{x_{ij}\}}{\max\{x_{ij}\} - \min\{x_{ij}\}} * a + (1-a), \tag{3.2}$$

Where x_{ij}^* represents the membership degree of the ith item under the jth method. The parameter a represents the attitude preference of the decision-maker and is usually set to 0.9.

(2) Calculate the fuzzy frequency p_{hj} of the ith indicator at the hth evaluation level:

$$p_{hi} = \sum_{j=1}^{m} \delta_{hi} x_{ij}^*, \tag{3.3}$$

Where m is the number of single evaluation methods used. If the ith item is in the hth evaluation level, then $\delta_{hi} = 1$; otherwise, $\delta_{hi} = 0$.

(3) Calculate the fuzzy frequency W_{hi} of the ith item at the hth evaluation level:

$$W_{hi} = \frac{p_{hi}}{\sum_h p_{hi}}, \tag{3.4}$$

Where W_{hi} represents the difference in evaluation scores obtained from the single evaluation model.

(4) Convert the ranking position into a score Q_{hi}:

$$Q_{hi} = \frac{(q-h)(q-h+1)}{2}, \tag{3.5}$$

Where Q_{hi} is the score of the ith item in the hth evaluation level, and q is the total number of evaluation items.

(5) Calculate the fuzzy Borda score B_i for the ith item:

$$B_i = \sum W_{hi} Q_{hi}. \tag{3.6}$$

Step 4. Validation of the rationality of the combined evaluation results.

The combined calculation results and the calculation results of the individual evaluation methods are re-entered into Equation ((3.1)). If the combined evaluation results do not pass the consistency test, it indicates that the selected individual evaluation methods in this study are not reasonable, and new individual evaluation methods need to be selected. If the new Kendall consistency coefficient is greater than or equal to 0.8, the combined evaluation results are considered more rational.

The flowchart of the proposed model in this study is shown in Figure 1.

4. Case study

4.1. **Project overview.** The total contracted area of the South Nanchang Joy City commercial project in China is 42,886.52 m^2. The total area of the foundation pit for this project is 38,427 m^2, with a total length of 810 m. Depending on the site elevation, surrounding environment, and geological conditions, the overall support method employed is bored piles + CSM (Cement Sand Mixing) walls + steel supports (localized concrete supports). The minimum clear distance between the basement of this project and the main structure of the Guanzhou Station on Line 4 is 35.8m, and the minimum clear distance from the basement to the auxiliary structure is approximately 12.4 m. The minimum clear distance from the basement to the centerline of Yunjin Road is 24.0 m.

Five subcontractors participated in the deep foundation pit support project for this project. The basic information of these five subcontractors is shown in Table 2.

This project belongs to a typical engineering general contracting project on a large scale. The construction quality of subcontractors directly affects the safety of the project, which is of great practical significance. Moreover, the number of potential subcontractors is appropriate, making the project highly representative. According to this article's proposed evaluation model for subcontractors in the construction industry, two types of data need to be collected for the case study. (1) Data for

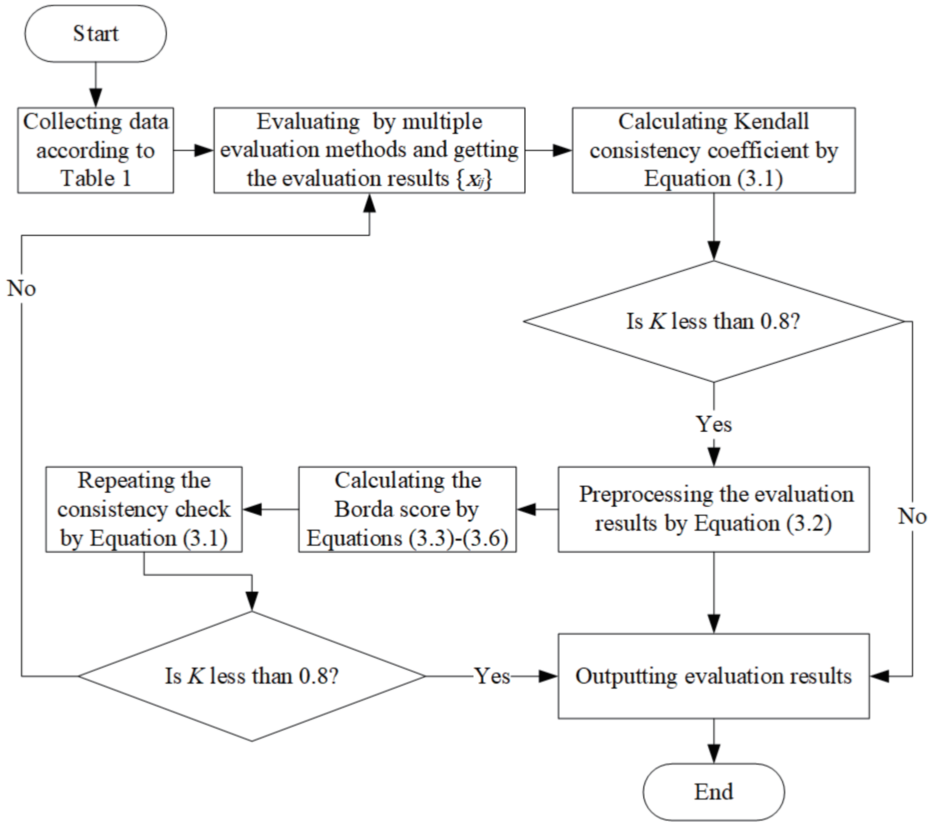

FIGURE 1. Flowchart of the proposed model in this study

TABLE 2. Basic information of subcontractors

Subcontractors	Qualification	Project schedule (Day)	Unit price (RMB/m)
P_1	Professional contracting qualification for municipal engineering, level two.	90	583.82
P_2	General contracting qualification for construction projects, level three.	85	427.25
P_3	General contracting qualification for construction projects, level two.	88	650.00
P_4	General contracting qualification for construction projects, level three.	80	492.44
P_5	General contracting qualification for construction projects, level three.	86	398.99

calculating weights in the AHP method, (2) Evaluation information for calculation with multiple evaluation methods.

4.2. **Weight Calculation.** This study utilized a questionnaire survey to collect data for weight calculation. Six engineering experts were invited to compare the relative importance of each indicator at the same hierarchical level for primary, secondary, and tertiary indicators. Quantitative analysis was conducted using a 1-9 scale method. Four experts are from the general contracting company, and two experts are from related consulting firms. After calculations using the Super Decisions software, the weight calculation results based on the AHP method are shown in Table 3. This weight result will be used for subsequent evaluation methods.

4.3. **Subcontractor evaluation based on fuzzy Borda.** In Table 1, qualitative indicators were collected using questionnaire surveys to gather indicator data, while quantitative indicators were obtained through methods such as on-site surveys and reviewing relevant materials to collect data for the indicators.

In this study, four methods, namely fuzzy mathematics [5], physical element analysis [12], grey analysis [13], and set pair analysis [14], were selected to evaluate five subcontractors. The calculation principles and procedures of the four classic evaluation methods refer to the corresponding references. In this study, the evaluation results of subcontractors in the construction industry are divided into five levels. "Excellent" ($[80, 100]$) represents that the subcontractor has performed exceptionally well in project execution and has made significant contributions to the success of the project. "Good" ($[60, 80)$) represents that the subcontractor has performed well in project execution, meeting the required standards for the project. "Satisfactory" ($[40, 60)$) represents that the subcontractor has met the basic requirements in project execution but lacks outstanding abilities and performance. "Needs Improvement" ($[20, 40)$) indicates that the subcontractor has some areas for improvement in project execution and requires enhancements and upgrades. "Unsatisfactory" ($[0, 20)$) indicates that the subcontractor significantly fails to meet the requirements in project execution, unable to meet the basic standards, and may require replacement or termination of the cooperation. The evaluation results of the four algorithms are shown in Table 4.

Table 3. Weight calculation results based on AHP

Primary index	Weight	Secondary index	Weight	Tertiary index	Weight
X_1	0.714	X_{11}	0.458	X_{111}	0.221
				X_{112}	0.074
				X_{113}	0.050
				X_{114}	0.055
				X_{115}	0.055
		X_{12}	0.256	X_{121}	0.057
				X_{122}	0.043
				X_{123}	0.036
				X_{124}	0.120
X_2	0.286	X_{21}	0.104	X_{211}	0.049
				X_{212}	0.032
				X_{213}	0.023
		X_{22}	0.182	X_{221}	0.031
				X_{222}	0.050
				X_{223}	0.019
				X_{224}	0.062
				X_{225}	0.023

TABLE 4. Evaluation results by four single evaluation methods

Subcontractors	FCM		MEA		GA		SPA	
	Evaluation result	Ranking	Evaluation result	Ranking	Evaluation result	Ranking	Evaluation result	Ranking
P_1	61.89	4	68.38	2	70.67	3	63.67	4
P_2	86.57	1	81.44	1	80.26	1	84.05	1
P_3	75.09	3	55.70	5	53.89	5	65.27	3
P_4	75.74	2	66.26	3	73.37	2	79.13	2
P_5	60.47	5	65.69	4	60.10	4	53.74	5

By plugging the evaluation results of the four methods into Equation (3.1), it can be calculated that $K = 0.775 < 0.8$. This indicates that their consistency is relatively weak and there are significant differences among them. Therefore, a combined evaluation is needed. The evaluation results from Table 4 were sequentially input into Equations (3.2)-(3.6) to calculate the fuzzy Borda values for each criterion, which were determined to be 0.059506, 0.064943, 0.052615, 0.062212 and 0.045298, respectively. The fuzzy Borda values have been reprocessed to the range $[[0, 100]$, and the calculated results are shown in Table 5.

TABLE 5. Evaluation results

Subcontractors	Proposed model	
	Evaluation result	Ranking
P_1	72.79	3
P_2	79.44	1
P_3	64.36	4
P_4	76.10	2
P_5	55.41	5

The ranking of all evaluation methods is shown in Figure 2. From the combined evaluation results, it can be seen that P_2 and P_4 ranks higher in the combined ranking results. The ranking of the fuzzy Borda method in the combination is only slightly different from the ranking of the four individual evaluation models (with a fluctuation of one position). However, based solely on the data, it cannot be determined whether the combined evaluation results are closely related to the original evaluation results. Therefore, it is necessary to verify the evaluation results of the combined evaluation model. By substituting the five evaluation results from Table 4 back into Equation (3.1) and calculating, it can be determined that $K = 0.824 > 0.8$, This indicates that their consistency meets the requirements. By comparing the evaluation results of the score and ranking between the individual evaluation models and the combined model, it can be observed that the ranking of the five methods is generally consistent. This indicates that the combination evaluation model based on the fuzzy Borda method is feasible in the evaluation of subcontractors in the field of construction engineering. The project ultimately selected subcontractor P_2, which aligns with the results of the combined evaluation, thus validating the consistency between the evaluation results and the actual situation of the project. This method incorporates the advantages of two individual evaluation methods, while also considering the interrelationships between indicators and the discrete characteristics of the data. As a result, the evaluation results are more comprehensive and demonstrate clear rationality.

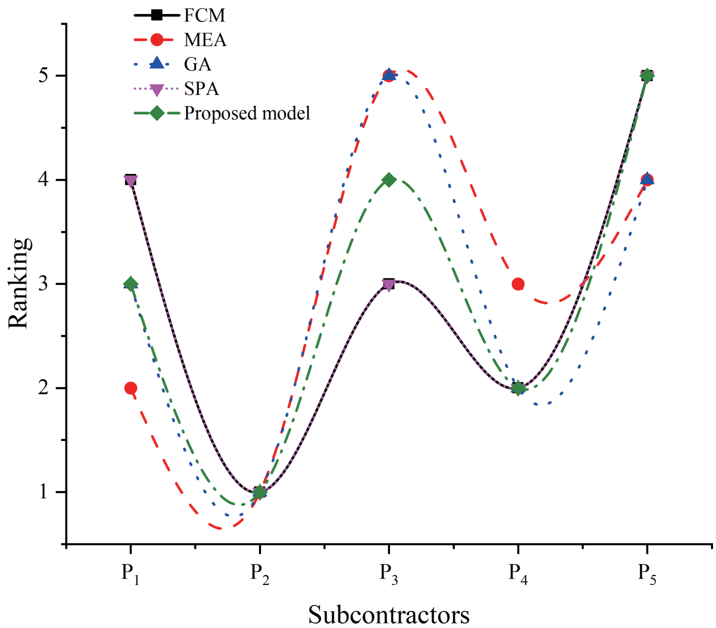

FIGURE 2. Ranking of all evaluation methods

Parameter a represents the manager's attitude preference. According to Equation (3.2), as the value of a approaches 1, the artificially corrected membership degree approaches 0, reflecting the manager's trust in a single evaluation result [15]. Currently, there is no parameter analysis for parameter a. Therefore, this study selects a=0.9, 0.8, ..., 0.2, and 0.1, and performs combination calculations in order. The calculation results are shown in Table 6.

TABLE 6. Impact of different managerial attitudes on portfolio evaluation results

a	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
K	0.824	0.824	0.824	0.768	0.768	0.768	0.707	0.707	0.707

From Table 6, it can be observed that as parameter a decreases, managers become increasingly distrustful of individual evaluation results. This leads to a greater disparity between portfolio evaluation results and individual evaluation results. When $a > 0.6$, the portfolio evaluation model proposed in this study becomes ineffective. Therefore, it is recommended to set the parameter a to be greater than or equal to 0.6 when using the evaluation model proposed in this study.

Based on the above case analysis, the selection of experts is critical for improving the scientific rigor of decision-making evaluation information. Their input contributes to the evaluation of this model. Furthermore, the general contracting decision-making management unit needs to draw on the decision-making experience of relevant projects. This will enhance the quality of the management decision-making team, promote the consideration of objective suggestions, and prevent subjective biases from influencing the selection of subcontractors in a scientific manner. Additionally, the choice of decision-making methods should be tailored to the specific circumstances of the project to avoid any drawbacks associated with the inappropriate use of a single method, which could compromise the accuracy of the decision-making process.

5. Conclusion

This paper proposes a novel evaluation model for subcontractors in the field of architectural engineering, based on the fuzzy Borda method. The model harmonizes the differences in results obtained from multiple evaluation methods by calculating the fuzzy Borda value. Empirical research demonstrates that the optimal subcontractor for this project is P_2, with an evaluation result of "Good", which is consistent with engineering practice. Compared to classical multi-attribute evaluation methods, this model addresses the limitations and variations of single evaluation methods in the evaluation of subcontractors in the field of construction engineering. It also avoids contradictory evaluation results from multiple evaluation schemes, thereby ensuring more accurate evaluation outcomes. It is recommended that the threshold value for the calculation parameters of this model should not be lower than 0.6. Further research is needed in the future to explore ways to reduce the computational complexity of the combined evaluation method.

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