Research Article

Private-Sector Partner Selection for Public-Private Partnership Projects Based on Improved CRITIC-EMW Weight and GRA -VIKOR Method

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When the government decides to use the public-private partnership (PPP) in projects, such as infrastructure construction, selecting a private-sector partner that meets the project's needs is one of the key factors for successful implementation, but this is ignored in existing research. On this basis, this paper proposes a GRA-VIKOR method based on the combined weight of the improved CRITIC-entropy weight method (EWM). The traditional CRITIC method is improved by combining it with EWM. The combined weights are measured, which reduces the limitations of the single weight. Considering the inherent correlation of evaluation indicators, the VIKOR method is combined with the grey relational analysis (GRA), which makes the results of the selection assessment more reasonable. This paper carries out a case study of the first inland navigation PPP project in China. Through preliminary tracking studies, it tests the effectiveness of the proposed method, the superiority of which is demonstrated by comparing the evaluation results with those of the traditional GRA methods, VIKOR, and TOPSIS.

1. Introduction

As China's economy enters a new normal, the demand for infrastructure is increasing, while the traditional direct investment and construction by the government can hardly meet the public requirement for quality infrastructure [1]. The proposed public-private partnership (PPP) provides a new approach for the government to alleviate the debt pressure, broaden financing channels, and improve public services, thus is widely adopted in China [2]. According to the annual report, by the end of 2021, China's cumulated PPP projects reached 13,359, and the total investment amount reached 193,758.837 billion yuan, an increase of 9.89%. Among them, there are 4,439 government-paid projects in total and 1,658 user-paid projects. In recent practice, a large number of PPP projects have failed due to poor financing, lack of experience, and unsatisfactory operation of the social capital [3, 4]. The root cause of this phenomenon is that the government does not rationalize the selection of social capital partners according to the characteristics of the project, which leads to a mismatch between supply and demand and fails to achieve the expected cooperation effect. In recent years, the Chinese government has paid more attention to this issue. For example, the Ministry of Finance promulgated Implementation Opinions on Promoting the Standardized Development of Government-Social Capital Cooperation in March 2019. Li et al. considered the selection of private-sector partners is one of the key factors to guarantee the successful implementation of the PPP project [5, 6]. Inappropriate partners are the prominent risk factors for PPP projects, which is precisely the most neglected problem [7]. Therefore, it is of great practical significance to study the partner selection for PPP projects.

So far, few studies have been carried out on private-sector partner selection in PPP projects, and most of the studies focus on the application of PPP in infrastructure construction. Private-sector partner selection is essentially

an integrated ranking of multiple alternatives under multiple evaluation criteria. Therefore, it is a multicriteria decision-making (MCDM) problem. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) and VIKOR method are used as effective tools to solve MCDM problems [8]. The VIKOR method is an effective tool for private-sector partner selection. However, the premise of the traditional VIKOR decision is limited information, which has the disadvantage of information omission [9]. Although existing studies have investigated the private-sector partner selection from various perspectives using different MCDM methods and achieved certain results, there are still limitations that need further improvement, which is reflected in the following two aspects: (1) the multiple attribute decision-making method applied in existing research does not consider the inherent correlation between the evaluation indicators of the selection, which cannot be solved by traditional MCDM methods. Thus, the information-digging of the indicators is insufficient, affecting the accuracy of the evaluation results; (2) the single method of determining the weights of the evaluation indicators ignores its own defects, which makes the weight allocation of the indicators not sufficiently reasonable.

To fill the shortage of existing research, this paper introduces the grey system theory into multiple attribute decision-making. Grey relational analysis (GRA) is used to explore the inherent correlation of decision indicators, and the grey relation is used to modify the aggregation function of the VIKOR method. It establishes a new GRA-VIKOR method to deal with private-sector partner selection. In terms of weight determination, the traditional CRITIC method uses standard deviation to measure the intensity of conflict among indicators, which leads to inconsistency in the base unit and the order of magnitude; thus, measurement distortion occurs [10]. The Gini coefficient is a reflection of the comparative intensity of indicators in MCDM, measuring the conflicting nature of each indicator [11]. In this paper, the improved CRITIC method is obtained by replacing the standard deviation with the Gini coefficient, which is used to measure the intensity of conflict among indicators. To avoid the limitations of a single weight, the improved CRITIC method is combined with the EWM to determine the combined weights of evaluation indicators, which solves the problem of insufficient rationality.

This paper is organized as follows: Section 2 reviews the relevant literature on the main research methods for multiple attribute decision-making and identifies the main contributions of this paper; Section 3 presents the specific steps of the proposed method; Section 4 conducts a case study of the first PPP project on inland waterway shipping in China to test the validity of the method and make a comparative analysis with traditional MCDM methods; Section 5 draws the conclusion.

2. Literature Review

Throughout the years, scholars have achieved certain results in studying private-sector partner selection for public-private partnership (PPP) projects, but the research in this field is still relatively insufficient. As described in Section 1, private-sector partner selection is a multicriteria decision-making (MCDM) problem. Therefore, the relevant research on MCDM problems is closely related to this study. The commonly used MCDM methods are Tomada de Decisão Iterativa Multicritério (TODIM), multiattributive border approximation area comparison (MABAC), the technique for order performance by similarity to ideal solution (TOPSIS), and VlseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR).

MABAC is the multiattribute border approximation area comparison, which ranks the alternatives for merit by comparing the distance of the alternatives to the border approximation area. Zhang and Wang [12] combined the Bayesian method with the Markov chain Monte Carlo (MCMC) method, applied them to the selection ranking, and validated this method by numerical examples. Zhang et al. [13] introduced an extended MABAC method to evaluate and select the optimal supplier in under picture fuzzy environment. Ghadikolaei et al. [14] proposed to select partners based on the decision made in a grey environment, using the combination of DEMATEL-based analytic network process (DANP) and MABAC techniques to establish a grey DANP-MABAC method for selection.

TODIM is based on the value function of prospect theory, which compares a solution with another one, calculates the relative superiority, and selects the optimal solution according to the superiority degree. Zhao et al. [15] applied the TODIM method to stock decision selection under uncertain information. Liu et al. [16] determined the criterion weights through the analytic network process (ANP) and applied TODIM to the selection of suppliers for nuclear power equipment. Tian et al. [17] applied the TODIM method to select green suppliers considering the ambiguity of evaluation information and the psychological state of decision makers during the selection.

TOPSIS is an objective selection method that ranks the choices by performing distance measures with the best and worst solutions. Venkatesh et al. [18] used the fuzzy analytic hierarchy process (FAHP) to calculate criterion weights and to establish a fuzzy AHP-TOPSIS-based selection. Due to the complexity and uncertainty of alternatives and the fuzziness of information, fuzzy sets were introduced, and a TOPSIS-based multipartner classification model [19] was proposed. Wu et al. [20] proposed an integrated decision-making model from a sustainable perspective by applying the TOPSIS method using trapezoidal fuzzy numbers to calculate the weights of different decision makers. The combination of the GRA with the TOPSIS method has also been effectively applied. Naseem et al. [21] designed a GRA-TOPSIS selection evaluation method. Wang et al. [22] introduced the fuzzy theory and used the FTOPSIS model to rank the alternatives.

VIKOR is a compromise ranking method to rank alternative decisions by maximizing group utility and minimizing individual regret, which is also an effective method to study multicriteria decision making (MCDM) problems. Yin and Li [23] introduced the fuzzy prospect theory, calculated criterion weights by entropy evaluation, and applied VIKOR

TABLE 1: Principles and characteristics of main research methods.

No.	Methods	Principles	Characteristics
1	TODIM	By comparing any two solutions, the dominance matrix is constructed. The dominance of individuals is assembled to form the overall dominance, and the ranking is based on the dominance	The effect evaluation must be a specific value. It cannot evaluate the situation where the effect value is an interval value
2	MABAC	The border matrix is calculated based on the decision matrix. Then, the distance of each alternative from the border approximation area is used to rank the alternatives for selection	The computational process is simple, and the results are stable. It is easy to combine with other methods and does not reflect the decision maker's preference
3	TOPSIS	It is a sequential selection ranking technique of ideal similarity, which obtains the optimal selection by determining the solution with the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution	It has the advantages of robust logical structure, simple computation, and considering both ideal and negative-ideal solutions. It is suitable for multiple attribute decision-making based on the full rationality of decision makers
4	VIKOR	A compromise ranking method that determines positive and negative-ideal solutions. It performs compromise ranking of finite decision alternatives by maximizing group utility and minimizing individual regret	With the characteristics of considering both group utility maximization and individual regret minimization and incorporating decision makers' subjective preferences, it has higher stability and credibility of the ranking

for selection sort. Garg and Sharma [24] proposed a combined model based on best-worst evaluation and ranking and used VIKOR for the final selection of partners. As the research progressed, some extensions were gradually developed. Lam et al. [25] combined entropy evaluation with the VIKOR method. Zhou et al. [26] combined the best-worst method (BWM) and information entropy for subjective and objective assignment and used the VIKOR method to assemble and rank the evaluation information for selection. As shown in Table 1, the VIKOR method has the advantage of considering both the maximization of group utility and the minimization of individual regret and incorporating the subjective preferences of decision makers. Therefore, it has higher ranking stability and credibility.

Based on existing research results, TOPSIS and VIKOR are the two main multi-criteria decision-making (MCDM) methods, and a large number of studies have proved their effectiveness. Different types of PPP projects have different requirements for partners, which makes decision makers have different preferences. The characteristics of the research methods in Table 1 show that VIKOR best fits the private-sector partner selection studied in this paper. Therefore, this paper chooses VIKOR as the main research method to study private-sector partner selection in public-private partnership (PPP). At present, no research in this field has considered the inherent correlation between the selection evaluation indicators. Based on previous studies, this paper combines VIKOR with the GRA to establish a new GRA-VIKOR decision-making method to solve the private-sector partner selection problem in PPP projects. In terms of determining the weights of indicators, combine the CRITIC method and EWM to verify the effectiveness of combined weights [27, 28]. But neither of them considered the inconsistency in the base unit and the order of magnitude due to standard deviation. On this basis, this paper improves the CRITIC method by introducing the Gini coefficient to replace the standard deviation, and a new CRITIC-EWM is obtained, which is then used as the method for determining the weights of the indicators.

3. Methodology

3.1. Research Framework. To investigate private-sector partner selection for public-private partnership (PPP) projects, this paper proposes an improved CRITIC-entropy weight method (EWM) and GRA-VIKOR method. The research framework consists of three parts, as shown in Figure 1. The first part reviews and summarizes existing research results and proposes the research method. In the second part, the improved CRITIC-EWM is used to calculate the weights of evaluation indicators. In the third part, the GRA-VIKOR method is developed to make a selection sort.

3.2. Normalization of Indicators. Suppose the selection evaluation system contains n objects and m indicators. The former constitutes the set of options $E = \{E_1, E_2, \cdots, E_n\}$, and the latter constitutes the set of indicators $F = \{F_1, F_2, \cdots, F_m\}$. The attribute value of the indicator F_j corresponding to the object E_i is $c_{ij}, i = 1, 2, \cdots, n; j = 1, 2, \cdots, m$. The evaluation matrix is $C = \{c_{ij}\}_{n \times m}$. The decision matrix $S = \{s_{ij}\}_{n \times m}$ can be obtained by normalizing c_{ij}, and it is calculated as follows:

$$\text{Benefit} - \text{based indicators } s_{ij} = \frac{c_{ij} - \min_i c_{ij}}{\max_i c_{ij} - \min_i c_{ij}} \quad (1)$$

$$(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m),$$

$$\text{Cost} - \text{based indicators } s_{ij} = \frac{\max_i c_{ij} - c_{ij}}{\max_i c_{ij} - \min_i c_{ij}} \quad (2)$$

$$(i = 1, 2, \cdots, n; j = 1, 2, \cdots, m).$$

3.3. Combined Weight Calculation. CRITIC is an objective weighting method that can measure the intensity of
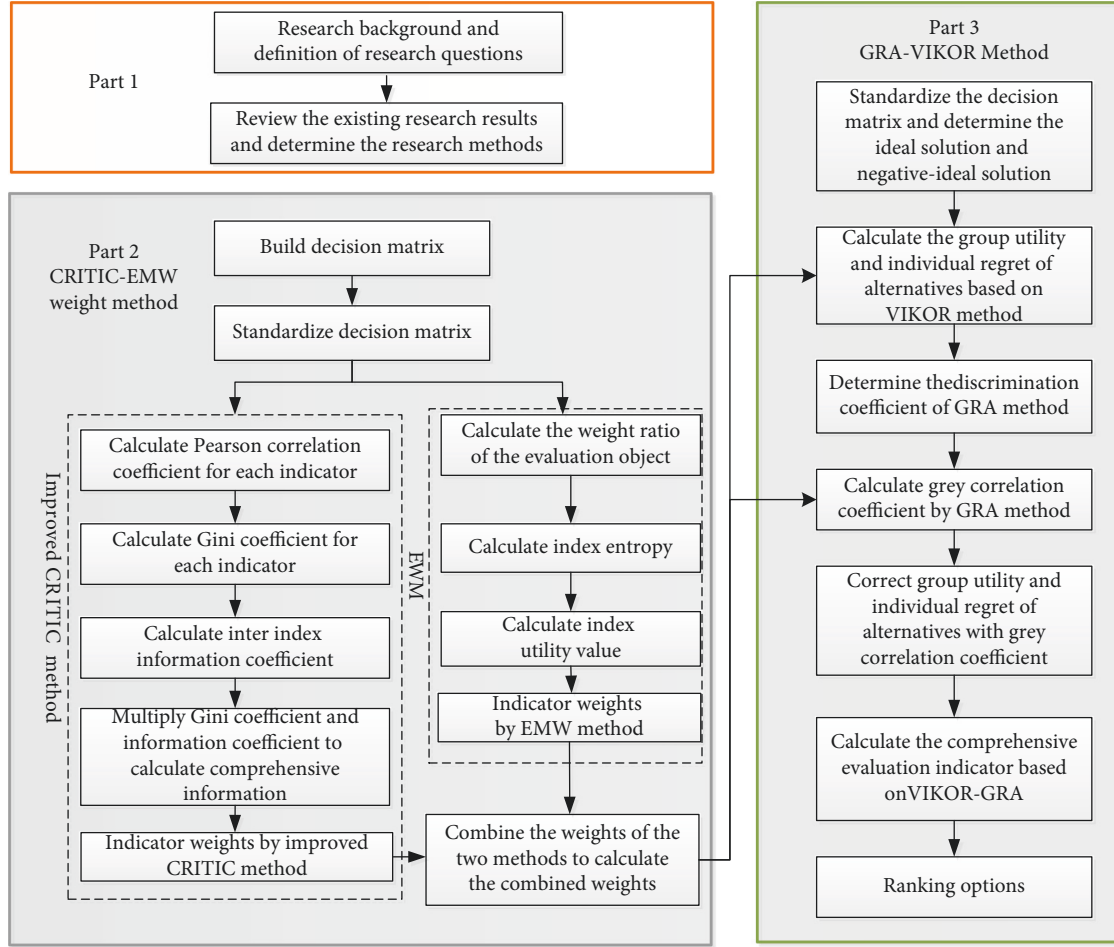
Figure 1: Research framework.

comparison between indicators but not the effect of dispersion [29]. Precisely, the entropy weight method (EWM) determines the weight of an indicator based on the degree of dispersion among the indicators. The combination of the two methods reflects the indicator weights more reasonably. Therefore, in this paper, we choose to combine the improved CRITIC method and EWM to determine the combined weights of grey relations.

3.3.1. The Improved CRITIC Method. The CRITIC method reflects the variability and inherent conflict among indicators through the standard deviation and correlation coefficient. Traditionally, the correlation coefficient may be negative, which leads to wrong results. When the base unit and order of magnitude of the data are different, there will be distortion in the calculation results. To solve the above problems, this paper takes the absolute value of the correlation coefficient and introduces the Gini coefficient instead of the standard deviation to measure the conflict between indicators and obtains the improved CRITIC weight calculation method.

   Step 1. Calculate the correlation coefficient matrix.

Suppose $X = \left\{ x_{ij} \right\}_{n \times m}$ is the correlation coefficient matrix calculated, and x_{ij} is the Pearson correlation coefficient. It is calculated as follows:

$$x_{ij} = \frac{\sum_{k=1}^{n} \left(s_{ik} - \overline{s}_i \right) \left(s_{jk} - \overline{s}_j \right)}{\sqrt{\sum_{k=1}^{n} \left(s_{ik} - \overline{s}_i \right)^2} \cdot \sqrt{\sum_{k=1}^{n} \left(s_{jk} - \overline{s}_j \right)^2}}, \quad (3)$$

where $\overline{s}_i, \overline{s}_j$ are the average of indicators i and indicators j, respectively.

Step 2. Calculate the Gini coefficient.

Suppose ε_j is the Gini coefficient used to measure the indicator information distribution. It is calculated as follows:

$$\varepsilon_j = \frac{\sum_{i=1}^{n} \sum_{k=1}^{n} \left| s_{ij} - s_{kj} \right|}{2n \sum_{i=1}^{n} s_{ij}} \ (j = 1, 2, \ldots, m). \quad (4)$$

It can be seen from the equation that $\varepsilon_j \in [0, 1]$. The closer ε_j is to 1, the more unbalanced the information distribution is, and the more information it contains; the closer ε_j is to 0, the more balanced the information distribution is, and the less information it contains.

Step 3. Calculate the information coefficient.

Suppose γ_j is the information coefficient. There are positive and negative correlations between indicators. To ensure calculation accuracy, it takes the absolute value of the Pearson coefficient, which is then brought into the calculation of the information coefficient. It is calculated as follows:

$$\gamma_j = \sum_{i=1}^{n} \left(1 - \left|x_{ij}\right|\right)(j = 1, 2, \ldots, m). \tag{5}$$

Step 4. Calculate the general quantities of information of indicators.

Suppose η_j is the general quantities of information of indicators j. It is calculated as follows:

$$\eta_j = \varepsilon_j \cdot \gamma_j \,(j = 1, 2, \ldots, m). \tag{6}$$

Step 5. Calculate the weight of indicators as follows:

$$W_j^1 = \frac{\eta_j}{\sum_{j=1}^{m} \eta_j} \,(j = 1, 2, \ldots, m), \tag{7}$$

where $\sum_{j=1}^{m} W_j^1 = 1$, $0 \le W_j^1 \le 1$

3.3.2. The Entropy Weight Method (EWM)

Step 1. Calculate the weight ratio of the object.

Suppose the weight ratio is f_{ij}. It is calculated as follows:

$$f_{ij} = \frac{s_{ij}}{\sum_{i=1}^{n} s_{ij}} \,(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m). \tag{8}$$

Step 2. Calculate the entropy.

Suppose the entropy is e_j. It is calculated as follows:

$$e_j = -\frac{1}{\ln m} \cdot \sum_{i=1}^{n} s_{ij} \ln s_{ij} \,(j = 1, 2, \ldots, m). \tag{9}$$

Step 3. Calculate the weight

Use EWM to calculate the weight of indicators j as follows:

$$W_j^2 = \frac{1 - e_j}{\sum_{i=1}^{n} \left(1 - e_j\right)} = \frac{1 - e_j}{m - \sum_{i=1}^{n} e_j} \,(j = 1, 2, \ldots, m), \tag{10}$$

where $\sum_{j=1}^{m} W_j^2 = 1$ and $0 \le W_j^2 \le 1$.

3.3.3. Combined Weights.

The combined weight of W_j^1 and W_j^2 is the following:

$$W_j = \frac{W_j^1 \cdot W_j^2}{\sum_{j=1}^{m} W_j^1 \cdot W_j^2} \,(j = 1, 2, \ldots, m), \tag{11}$$

μ is the coefficient of the weight combination, where $\mu \in [0, 1]$. In this paper, it is set as $\mu = 0.5$

3.4. The GRA-VIKOR Method.

VIKOR is a multicriteria decision-making (MCDM) method based on ideal ranking. The premise of the traditional VIKOR method is limited information, which has the disadvantage of information omission. In order to fully explore the data of the indicators, this paper adopts grey relational analysis (GRA) to explore the inherent rules of the decisive indicators, considers the inherent correlation between the evaluation indicators, and combines the grey relational coefficient with the group utility value and individual regret value of the VIKOR method to improve the accuracy of the evaluation results.

Step 1. Calculate the ideal sequence.

Assume that s_{0j}^+ and s_{0j}^- are the ideal solution and negative-ideal solution, respectively; they are composed of cost-based indicators and benefit-based indicators in the decision matrix as follows:

$$S^+ = \left(s_1^+, s_2^+, \cdots, s_m^+\right) S^- = \left(s_1^-, s_2^-, \cdots, s_m^-\right)$$
$$s_j^+ = \left\{\max_i s_{ij} | j \in I, \min_i s_{ij} | j \in O\right\} \tag{12}$$
$$s_j^- = \left\{\max_i s_{ij} | j \in O, \min_i s_{ij} | j \in I\right\},$$

where I is the benefit-based indicator and O is the cost-based indicator.

Step 2. Calculate the group utility and individual regret of alternatives as follows:

$$Q_i = \sum_{i=1}^{n} w_j \left(s_j^+ - s_{ij}\right) / \left(s_j^+ - s_j^-\right), j = 1, 2, \ldots, m, \tag{13}$$

$$R_i = \max_j \left\{w_j \left(s_j^+ - s_{ij}\right) / \left(s_j^+ - s_j^-\right)\right\}, j = 1, 2, \ldots, m. \tag{14}$$

The higher the value of Q_i is, the lower the group utility of the alternative firms is; the higher the R_i value is, the lower the individual regret of the alternative firms will be.

Step 3. Determine the discrimination coefficient of the grey relation.

In most grey relational models, the coefficient of discrimination is fixed at 0.5. However, it reflects the influence of the maximum difference between the two extremes of the indicator on the grey relational coefficients, which will be different depending on the value of the coefficient of discrimination. If the derived grey relation values are similar, it is difficult to distinguish them if the differentiation of the comparative series is small. The principle of selecting the discrimination coefficient should be to make the grey relational values as large as possible. In this paper, the discrimination coefficient is determined by setting a range of the coefficient using absolute deviation.

Assume that Δ_s is the average absolute deviation, B_Δ is the ratio of absolute deviation to the maximum absolute deviation, and ρ is the discrimination coefficient. They are calculated as follows:

$$\Delta_s = \frac{1}{nm} \sum_{i=1}^{n} \sum_{j=1}^{m} \left| s_{0j} - s_{ij} \right|,$$

$$B_\Delta = \frac{\Delta_s}{\max_i \max_j \left| s_{0j} - s_{ij} \right|}. \tag{15}$$

Value range of resolution coefficient ρ:

When $B_\Delta < 1/3$, $\rho \le 1.5\Delta_s$; when $B_\Delta \ge 1/3$, $\rho > 1.5\Delta_s$,

Step 4. Calculate the grey relational coefficient as follows:

$$\xi_{ij}^+ = \frac{\min_i \min_j \left| s_{ij} - s_j^+ \right| + \rho \max_i \max_j \left| s_{ij} - s_j^+ \right|}{\left| s_{ij} - s_j^+ \right| + \rho \max_i \max_j \left| s_{ij} - s_j^+ \right|}$$

$$(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m),$$

$$\xi_{ij}^- = \frac{\min_i \min_j \left| s_{ij} - s_j^- \right| + \rho \max_i \max_j \left| s_{ij} - s_j^- \right|}{\left| s_{ij} - s_j^- \right| + \rho \max_i \max_j \left| s_{ij} - s_j^- \right|} \tag{16}$$

$$(i = 1, 2, \ldots, n; j = 1, 2, \ldots, m).$$

Step 5. The group utility and individual regret based on GRA are $\widetilde{Q}_i$ and $\widetilde{R}_i$, respectively, as follows:

$$\widetilde{Q}_i = Q_i \sum_{j=1}^{m} \xi_{ij}^+ \cdot w_j \, (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m), \tag{17}$$

$$\widetilde{R}_i = R_i \max_j \xi_{ij}^- \cdot w_j \, (i = 1, 2, \cdots, n; j = 1, 2, \cdots, m). \tag{18}$$

Step 6. Calculate the comprehensive evaluation indicator based on VIKOR-GRA as follows:

$$\widetilde{T}_i = \theta \left(\frac{\widetilde{Q^*} - \widetilde{Q}_i}{\widetilde{Q^*} - \widetilde{Q^-}} \right) + (1 - \theta) \left(\frac{\widetilde{R^*} - \widetilde{R}_i}{\widetilde{R^-} - \widetilde{R*}} \right), i = 1, 2, \ldots, n, \tag{19}$$

where $\widetilde{Q^*} = \max_i \widetilde{Q}_i$, $\widetilde{Q^-} = \min_i \widetilde{Q}_i$, $\widetilde{R^*} = \max_i \widetilde{R}_i$, $\widetilde{R^-} = \min_i \widetilde{R}_i$, θ is the preference coefficient, which satisfies $\theta \in [0, 1]$, and generally has $\theta = 0.5$.

Step 7. Determine the ranking of alternative enterprises.

Assume that the best cooperative enterprise is P_1 and the second best is P_2, ranked according to the maximum group

utility $\widetilde{Q}_i$. The optimal solution is when the enterprise meets the following two conditions:

Condition I: $\widetilde{T}(P_1) - \widetilde{T}(P_2) \ge GT, GT = 1/(n - 1)$

Condition II: the optimal cooperative enterprise P_1 at least ranks the first in one of $\widetilde{Q}_i$ and $\widetilde{R}_i$

The determination of the optimal cooperative enterprise is based on the above two conditions, and the criteria are as follows:

(1) If both Conditions I and II are true, P_1 is the optimal enterprise.

(2) If only Condition I holds, both P_1 and P_2 are the best choices.

(3) If only Condition II holds, any alternatives that do not satisfy Condition I are optimal choices.

4. Case Study

4.1. Case Profile and the Evaluation Indicators Construction. The Xiaoqinghe River Recovery of Navigation Project is the first inland navigation PPP project in China. It is the first water conservancy project with a single investment of more than 10 billion yuan ever in Shandong Province. The project adopts the public-private partnership for operation. In the early stage, the government negotiated with several enterprises, four of which became alternatives. Scientific and reasonable indicators are the key factor for the selection and evaluation of cooperative enterprises. Under the basic principles of simplicity, systematicity, and pertinence, the government sets evaluation indicators from the perspectives of enterprise operation, economic rationality, and social recognition according to the characteristics and needs of this project. Relevant information is shown in Table 2.

The data of the cases in this paper were obtained from government research on the situation of each alternative enterprise, as shown in Table 3.

4.2. The Process and Results of Selection and Evaluation

4.2.1. Data Processing. The evaluation indicators of the decision matrix were analyzed. Q1, E4, and S2 were cost-based indicators; the smaller, the better. Q2, Q3, Q4, E1, E2, E3, and S1 were benefit-based indicators; the larger, the better. The decision matrix was normalized according to equation (1).

The ideal solution and negative-ideal solution are as follows:

$$S = \begin{bmatrix} 0.5055 & 0.2824 & 0.3181 & 0.5406 & 0.4788 & 0.5147 & 0.3811 & 0.4976 & 0.1676 & 0.3604 \\ 0.4676 & 0.6217 & 0.7262 & 0.7433 & 0.5456 & 0.4922 & 0.7342 & 0.5290 & 0.8941 & 0.6350 \\ 0.5252 & 0.4633 & 0.2317 & 0.2027 & 0.4624 & 0.3880 & 0.4043 & 0.4657 & 0.1397 & 0.3947 \\ 0.5000 & 0.5649 & 0.5637 & 0.3379 & 0.5092 & 0.5850 & 0.3902 & 0.5056 & 0.3912 & 0.5578 \end{bmatrix}. \tag{20}$$

TABLE 2: The evaluation indicator system of each alternative enterprise and interpretations.

No.	Categories	Indicators	Interpretations	Attribute
1		Q1: Debt-to-assets ratio (%)	Reflecting the assets of the enterprise	−
2	Quality indicators (Q)	Q2: The number of implemented water conservancy projects	Reflecting the enterprise's experience in similar projects	+
3		Q3: Times of winning the bid for 5-billion-scale PPP projects	Reflecting the enterprise's experience in similar modes	+
4		Q4: The number of qualifications owned	Reflecting whether the enterprise has the comprehensive strength to implement the project	+
5		E1: The scale of financing required for the project (billion yuan)	Reflecting the enterprise's capital gap	+
6	Economic indicators (E)	E2: The amount of credit granted by financial institutions (billion yuan)	Reflecting the confidence of financial institutions in the enterprise	+
7		E3: The amount of annual newly signed contract (billion yuan)	Reflecting the overall business scale of the enterprise	+
8		E4: Cumulative government subsidies during the operation period (billion yuan)	Reflecting the cost of government expenditure	−
9	Social recognition indicators (S)	S1: Times of winning the annual national quality engineering awards	Reflecting the recognition of the community and industry	+
10		S2: Number of environmental accident penalties	Water conservancy projects have high requirements for environmental protection. This indicator reflects the environmental compliance of the enterprise	−

TABLE 3: Initial evaluation indicators of each alternative enterprise.

No.	Alternative enterprises	Q1	Q2	Q3	Q4	E1	E2	E3	E4	S1	S2
1	P_1	75.6	164	92	8	51.25	80	10561	129.7	6	42
2	P_2	69.93	361	210	11	58.4	76.5	20344	137.9	32	74
3	P_3	78.55	269	67	3	49.5	60.3	11204	121.4	5	46
4	P_4	74.77	328	163	5	54.5	90.93	10812	131.8	14	65

TABLE 4: Weight coefficients of each evaluation indicator.

No.	Weight	Indicators									
		Q1	Q2	Q3	Q4	E1	E2	E3	E4	S1	S2
1	W_j^1	0.0637	0.0858	0.0712	0.0780	0.0671	0.0977	0.0821	0.179	0.0714	0.2041
2	W_j^2	0.0815	0.0644	0.0942	0.0848	0.0927	0.0662	0.2125	0.0772	0.1453	0.0812
3	W_j	0.0726	0.0751	0.0827	0.0814	0.0799	0.0819	0.1473	0.1281	0.1080	0.1426

The ideal solution and negative-ideal solution are as follows:

$$s_j^+ = \{0.4676, 0.6217, 0.7262, 0.7433, 0.5456, 0.5850, 0.7342, 0.4657, 0.8941, 0.3604\}$$

$$s_j^- = \{0.5252, 0.2824, 0.2317, 0.2027, 0.4624, 0.3880, 0.3811, 0.5290, 0.1397, 0.6350\}.$$

$$(21)$$

4.2.2. Calculate the Weight of CRITIC-EWM. According to equations (2)–(11), the weight coefficients of the CRITIC method and the entropy weight method (EWM) were calculated, respectively, to determine the combined weight, which measures the importance of each evaluation indicator. The calculation results are shown in Table 4.

4.2.3. Calculate Relevant Data Based on the GRA-VIKOR Method. According to equations (13)–(18), the group utility

TABLE 5: Relevant data of the VIKOR-GRA model.

Alternative enterprises	Data of the VIKOR-GRA model			
	Q_i	R_i	$\tilde{Q}_i$	$\tilde{R}_i$
P_1	0.7338	0.1373	0.7691	0.1473
P_2	0.1445	0.0751	0.1322	0.0726
P_3	0.8577	0.1473	0.8605	0.1439
P_4	0.4328	0.1055	0.4980	0.1460
Max	0.8577	0.1473	0.8605	0.1473
Min	0.1445	0.0751	0.1322	0.0726

value and individual regret value of the traditional VIKOR method and the GRA-VIKOR method were calculated, as shown in Table 5.

4.2.4. Result Analysis. The data of each indicator of the model were brought into (19) to derive the evaluation results as a basis for the government to select partners. The results are shown in Table 6.

TABLE 6: Evaluation results.

Case calculation results	Alternative enterprises			
	P_1	P_2	P_3	P_4
$\tilde{T}_i$	0.9372	0.000	0.9774	0.7425
Selection sort	3	1	4	2

TABLE 7: Sensitivity analysis of the decision coefficient.

No.	θ	Alternative enterprises				Selection sort
		P_1	P_2	P_3	P_4	
1	0.0	1.0000	0.0000	0.9545	0.9826	$P_2 > P_3 > P_4 > P_1$
2	0.3	0.9624	0.0000	0.9681	0.8385	$P_2 > P_4 > P_1 > P_3$
3	0.5	0.9373	0.0000	0.9772	0.7424	$P_2 > P_4 > P_1 > P_3$
4	0.7	0.9122	0.0000	0.9863	0.6464	$P_2 > P_4 > P_1 > P_3$
5	1.0	0.8745	0.0000	1.0000	0.5023	$P_2 > P_4 > P_1 > P_3$

TABLE 8: Comparative analysis of the methods.

No.	Alternative enterprises	GRA		TOPSIS		VIKOR		GRA-VIKOR	
		Analysis results	Selection sort	Analysis results	Selection sort	Analysis results	Selection sort	Analysis results	Selection sort
1	P_1	0.6950	3	0.2861	4	0.9331	3	0.9373	3
2	P_2	0.9090	1	0.6600	1	0.5000	2	0.0000	1
3	P_3	0.6194	4	0.2892	3	1.000	4	0.9772	4
4	P_4	0.7125	2	0.2994	2	0.2381	1	0.7424	2

From Table 6, it can be concluded that P_2 is the best partner in this selection. Its evaluation result can be interpreted as that under the evaluation indicator system set by the government, the overall performance of P_2 best fits the project demand, making it the potential partner among all the enterprises evaluated by the government.

4.3. GRA-VIKOR Examination

4.3.1. The Influence of the Decision Coefficient θ on Results. The value of the decision coefficient θ represents the decision maker's preference. If $\theta > 0.5$ the decision maker prefers maximum group utility; if $\theta < 0.5$, the decision maker prefers minimum individual regret; if $\theta = 0.5$, the decision maker prefers a compromised solution. In order to analyze the influence of θ on the results, this paper selects different values $[0, 1]$ and conducts a sensitivity analysis. The results are shown in Table 7.

From the above results, it can be seen that, in this case, the value of the decision coefficient θ does not affect the ranking of alternative enterprises; that is, this ranking is not sensitive to the value of the decision coefficient and is stable.

4.3.2. Comparative Analysis of the Methods. In order to verify the superiority of the method proposed in this paper, this example is compared with the gray relational analysis (GRA), the TOSPSIS method, and the traditional VIKOR method. The results of the comparative analysis are shown in Table 8.
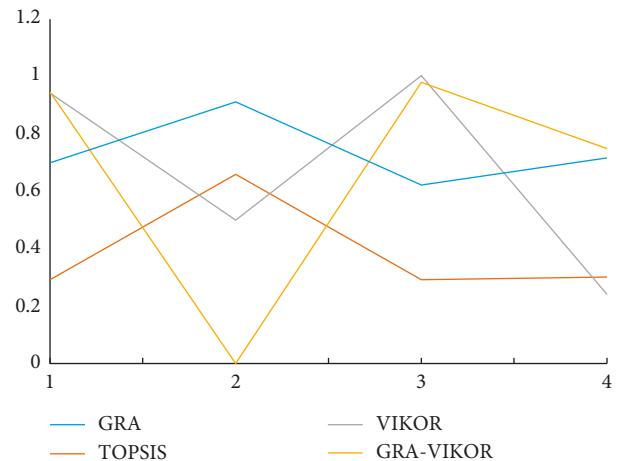

FIGURE 2: Comparative analysis of the results of different decision-making methods.

On the whole, many indicators of P_2 are the best among the alternative enterprises, making it most consistent with the government's demand, which is also verified by different evaluation methods. The four evaluation methods have basically consistent results, which proves the effectiveness of the method used in this paper. A comparative analysis (Figure 2) of the results of the four decision methods in Table 8 shows that the GRA-VIKOR method proposed in this paper has the greatest differentiation of the optimal solution, and the ranking is more reasonable considering the inherent correlation of the evaluation indicators. It verifies

the superiority of the proposed method in this paper over the traditional evaluation method.

5. Conclusion

This paper investigates the selection of potential social capital cooperation by the government before the implementation of public-private partnership (PPP) projects and proposes the GRA -VIKOR decision-making method based on the combined weights of the improved CRITIC-entropy weight method (EWM). The advantageous combination of VIKOR and grey relational analysis (GRA) solves the problem of correlation of evaluation indicators that cannot be solved by the traditional VIKOR method and makes multicriteria decision making (MCDM) more reasonable. The improved method realizes the full utilization of evaluation information, has more reasonable weights and provides an effective solution for the government to select cooperative enterprises in PPP projects. The main findings of this study are as follows:

(1) From the perspective of practical management, this paper aims to select the partner that best fits the PPP project and solve the problem of lacking a systematic and reasonable way of selecting social capital by the government before the implementation of the project. Based on the research results, the government can design a more suitable implementation plan and alternative social capitalist resource base to lay the foundation for the successful implementation of subsequent projects.

(2) At a theoretical level, the improved CRITIC method is combined with the entropy weighting method (EWM) to determine the combined weights, reduce the one-sidedness of single weighting, and obtain more reasonable weights. Using the advantages of grey relational analysis (GRA) in digging the information of evaluation indicators, we combine GRA with VIKOR to establish a new GRA-VIKOR method, which can make up for the shortcomings of VIKOR and provide an effective MCDM method.

(3) As for application and promotion, the first inland navigation PPP project in China is analyzed in this paper to prove the effectiveness of the proposed method. The superiority of the proposed method is verified by comparing the results with traditional MCDM methods. In addition, the proposed method can be applied not only to the selection problems studied in this paper but also to other fields, such as scheme comparison, safety assessment, and selection for supply chain partners. Meanwhile, using the research idea of this paper for reference, future studies can combine TOPSIS, TODIM, and MABAC with GRA, which needs further supplementation and improvement.

Data Availability

The data supporting the findings of the study are included within the paper.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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