An Improved Evaluation Model of Routes under the Influence of Offshore Wind Farms

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Abstract— In order to determine the optimal route in port waters under the influence of wind farms, the traditional evaluation system of routes was improved. Based on the influence of wind farms, the characteristics of port waters and the maritime data of relevant competent authorities, the influence of wind farms was determined as first level indicator. The TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) assessment model improved by the grey theo-ry was constructed, and the combinatorial weighting method was used to determine the weight of indicators. Taking the wind farms in Qinzhou Bay as an experimental object to evaluate the schemes of routes near the wind farms. The feasibility and effectiveness of the evaluation indicators system and evaluation model are verified. The results could be reference for the evaluation of routes in port water under the influence of wind farms.

Keywords: topsis; grey relational analysis; subjective and objective weighting method; wind farms; routes in port water; comprehensive evaluation

1. Introduction

As a permanent construction, wind farms will cause permanent changes to the navigable environment in the water[1]. It is mainly reflected in the following aspects: disturbing ship lookout, reducing the navigation area of ships, and increasing the complexity of traffic flow. Port waters always contain shipping channel, anchorage and other special navigable waters[2]. Due to the many reasons, such as frequent activity of ships, the crossing of routes, various types of ships, the risk of ship collisions in port waters is often higher compared with the exposed waters. Determining the best route in port water under the influence of wind farms is a complex multi-indicator evaluation problem. The area and location of the wind farms should be fully considered to ensure the safety of the ship navigation, and other factors should be considered to meet the navigation needs of most vessels in port waters, such as ship types, ship traffic flow tracks, anchorage sites and special navigable waters. The economy and efficiency of the route itself are also important factors for the evaluation.

At present, there are few studies on the evaluation of routes in port water under the influence of wind farms at home and abroad. The main research focuses on the in-fluences of wind farms on the navigation safety of ships, and on how to determine the safe distance between wind farms and the routes. On the study of the routes in the port water, the characteristics of the port waters

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are the main consideration, and the influence of the wind farms is not considered too much. Nie Yuanyuan et al [3] quantitatively obtained the safe distance range between routes and wind farms based on the collision probability. Han Dongyan [4] proposed that the port waters should follow the three principles of safety, standardization and integrity, and elaborated the basic theory of the route planning in port waters. Liu Jinxiu et al. [5] uses the fuzzy comprehensive evaluation method to establish an indicator system with natural conditions, channel parameters, technology and economy as the first-level indicator layer to optimize the navigation route of Qinzhou Port. Fan Zhongzhou et al. [6] uses the variation coefficient cloud element model to establish a ship collision risk indicator system with navigation route factors, natural environment factors, navigation environment factors and management factors as the first-level evaluation indicators to solve the problem of navigation route optimization.

According to the current study, it is necessary to establish a new indicator system to comprehensively evaluate the routes in port waters under the influence of offshore wind farms, so as to determine the best scheme and ensure the safe, orderly and efficient navigation of ships in the route. This study comprehensively considers the influence of wind farms on ship navigation and the particularity of port waters, and establishes a comprehensive evaluation indicator system according to the principle of multi-objective comprehensive evaluation. Based on the BWM-CRITIC weighting method, and the TOPSIS improved by grey correlation, the evaluation model is constructed，providing a reference for the evaluation of routes in port waters under the influence of offshore wind farms.

2. Establish the evaluation indicator system

As a large artificial navigation obstruction, when the ship is sailing in the nearby waters, affected by the wind flow or their own faults, improper operation may cause collision with the wind farms. In addition, the change of water navigation environment caused by wind farms will increase the probability of accidents. Therefore, the possibility of collision should be fully considered in the route planning and kept away from the accident-prone waters as far as possible[7].This paper focuses on the evaluation of routes in port water under the influence of wind farms. By reviewing the references [8-11] and the actual investigation of port waters, and consulting the experts of wind farms managers, senior captains, port authorities and other experts in related fields. Taking the influence of wind farms as the first-level indicator based on the principles of systematic, scientific and operable. Establishing an evaluation indictor system for routes in port waters under the influence of wind farms, see Table 1

Table 1 Evaluation index system of routes in port waters affected by wind farms

Evaluation goal	**First level**	**Second level**	**influence**
Evaluation of the routes in port waters under the influence of	The influence of wind farms B_1	The closest distance between the route and the wind farm C_1	positive
		Ratio of submarine cable length to wind farm width C_2	negative
		Disturbing of wind farms on ship	negative

wind farms A		communication and navigation equipment in the routes C_3	
		The influence of the wind farm on the ship lookout in the routes C_4	negative
	Parameters of routes B_2	The coverage degree of the existing traffic flow trajectory C_5	positive
		Maximum steering Angle C_6	negative
		Ratio of the route width to the maximum captain C_7	negative
		The degree of conflict between route and anchorage or other special navigable waters C_8	negative
	Hydro-meteorological factors B_3	the index describe the wind pushes away C_9	positive
		the index describe the flow pushes away C_{10}	negative
	economic factors B_4	The ratio of aquaculture cleaning area to route area C_{11}	negative
		The ratio of survey area for water depth to route area C_{12}	negative
	Organizational management factors B_5	Coverage degree of VTS C_{13}	positive
		Coverage degree of aids to navigation C_{14}	positive

3. Establish the evaluation model

3.1.Determine the set of evaluation criteria

The determination of the set of evaluation criteria requires specific engineering data. This paper refers to the relevant literature [12-15], combined with various legal documents and industrial technical standards, as well as the suggestions of the Dongying Maritime Safety Administration. The evaluation criteria were divided into 5 grades. Taking C1 as an example: according to the national general port plan of first-class open ports, the maximum type of ships arriving at the port in the long term is 50,000-ton ships. According to the Technical Guide for Navigation Safety Analysis of Offshore Wind Farm Site Selection (Trial), the representative ship is calculated to be 223 meters per the length of 50,000-ton bulk carrier in the General Design Code of Seaport, and the return diameter is calculated as 6 times the length. Calculating that the reference safety distance C between the wind farm and the route is about 2394m (1.3 nautical miles). According to the technical guide, the classification standard is given: C1≥15 nautical miles is excellent; 5 nautical miles > C1>2 nautical miles is good; C1> reference safety distance and <2 nautical miles is medium; C1 is poor between the minimum safety distance and reference safety distance; C1 <minimum safety distance is extremely poor. The specific classification criteria of each indicator are given, see Table 2.

Table 2 Set of evaluation criteria for routes

grades	**C_1/n mile**	**C_2**	**C_3**	**C_4**	**C_5/%**	**C_6/°**	**C_7**
I(excellent)	>5	<1	<2	<1	≥80	<20	(0,0.3]
II(good)	[2,5)	[1,1.5)	[2,3)	[1,2)	[60,80)	[20,40)	(0.3,0.5]
III(medium)	[1.3,2)	[1.5,2)	[3,5)	[2,3)	[40,60)	[40,50)	(0.5,0.8]
IV(poor)	[0.8,1.3)	[2,3)	[5,8)	[3,5)	[20,40)	[50,70)	(0.8,1.0]
V(poorest)	<0.8	≥3	≥8	≥5	<20	[70,90]	(1.0,1.3]
grades	**C_8**	**C_9**	**C_{10}**	**C_{11}**	**C_{12}**	**C_{13}/%**	**C_{14}/%**
I(excellent)	<0.1	≥0.6	≥0.6	<0.2	<0.05	≥90	≥60
II(good)	[0.1,0.2)	[0.4,0.6)	[0.4,0.6)	[0.2,0.5)	[0.05,0.1)	[80,90)	[50,60)
III(medium)	[0.2,0.4)	[0.2,0.4)	[0.2,0.4)	[0.5,0.7)	[0.1,0.2)	[70,80)	[40,50)
IV(poor)	[0.4,0.6)	[0.1,0.2)	[0.1,0.2)	[0.7,0.9)	[0.2,0.3)	[60,70)	[30,40)
V(poorest)	≥0.6	<0.1	<0.1	≥0.9	≥0.3	<60	<30

3.2.Combination weighting method

The best and worst method (BWM) is a subjective weighting method proposed by the Dutch scholar Rezaei[16]. It selects the most important and least important indicator from a series of indicators and compares them with the other indicators respectively to determine the weight. Compared with hierarchical analysis, it can simplify the empowerment process and reduce errors in data processing. Critic method is an objective weight assignment method proposed by Diakoulaki et al[17].This method reflects the amount of indicator information based on the conflict between the contrast intensity and indicator of the evaluation indicator. The greater the contrast intensity and conflict, the more the information amount, and the greater the weight of the cor-responding indicator. This paper combines the BWM method and the critic method to determine the subjective and objective weights, uses the game theory idea, and make the combination empowerment [18] to determine the optimal combination weight.

1) Determining the subjective weight: Select the most important indicator D_A and the least important indicator D_B ac-cording to the opinions of the expert group. The 1-9 point is used to determine the importance of the most important indicator compared with other indicators and the importance of other indicators versus the worst indicators. The corresponding scale was obtained by pairwise comparison, which are expressed as comparison vectors: $E_A = (e_{A1}, e_{A2}, \cdots, e_{An})$, $E_B = (e_{1B}, e_{2B}, \cdots, e_{nB})^T$. e_{Aj} represents the importance of the most important indicator D_A relative to the indicator D_j , e_{jB} represents the importance of the indicator D_j relative to the least important indicator D_B .1 indicates that both are equally important, 9 indicates that the former is extremely important for the latter, and .The weights are calculated as follows:

$$\min \xi \tag{1}$$

$$s.t.\begin{cases} |\,w'_A - e_{Aj}w'_j\,| \le \xi \\ |\,w'_j - e_{jB}w'_B\,| \le \xi \\ \sum_{j=1}^{n} w'_j = 1 \\ w'_j \ge 0 \end{cases} \tag{2}$$

w'_A is the value of the most important indicator, w'_B is the value of the least important indicator. w'_j is the subjective weight of the indicator . is the indicated value of the solved weight result.

*2) Determining the objective weight:*The critic method obtains the indicator weights by calculating the standard devia-tion and the correlation. The larger the standard deviation value, the greater the dif-ference between the indicators. Larger correlation values indicate lower independence between indicators and stronger association. The product result of contrast intensity and conflict represents the information of the indicator. The larger the information is, the more important it is to the indicator system, and the higher the weight of the cor-responding indicator is [19]. In the process of data processing, due to the different dimensions and units of the indicators, it needs to be treated with infinite dimensions, and then the weight of each indicator is calculated. For the positive indicator with the larger the better the value and the negative indicator with the smaller the better value, the standardized treat-ment formula is respectively:

$$u_{ij} = \frac{d_{ij} - d_{\min}}{d_{\max} - d_{\min}} \tag{3}$$

$$u_{ij} = \frac{d_{\max} - d_{ij}}{d_{\max} - d_{\min}} \tag{4}$$

$d_{\min} = d\min\left\{d_{1j}, d_{2j}, ..., d_{nj}\right\}$, $d_{\max} = d\max\left\{d_{1j}, d_{2j}, ..., d_{nj}\right\}$,according to the formula in literature [20]. Get the information quantity indicator T_j , and finally calculate the objective weight of the j indicator.

$$w_j = \frac{T_j}{\sum_{j=1}^{n} T_j} \tag{5}$$

*3) Determine the optimal weight:*Combinatorial weighting can not only reflect the intuitive evaluation of the im-portance of different indicators, but also reflect the objective law of data. By consider-ing the subjective and objective weight, find the consistency or compromise of the two, minimize the difference of the subjective and objective weight, and finally determine the comprehensive weight of each indicator [21].

$$w_3^T = F_1 w_1^T + F_2 w_2^T \tag{6}$$

w_1^T is the subjective weight vector. w_2^T is the objective weight vector. w_3^T is the optimal combination weight. F_1 and F_2 are combined coefficient of the main objective weight. According to the principle of game theory, the difference between the subjective and objective weight and the combination coefficient is minimized. According to the principle of matrix differentiation, obtaining the condition of optimizing the first derivative, and finally solve the combined coefficient of subjective and objective weights.

$$\min \left\| \sum_{v=1}^{2} F_v w_v^T - w_z^T \right\|_2 \quad (z = 1, 2) \tag{7}$$

$$\begin{bmatrix} w_1 \cdot w_1^T & w_1 \cdot w_2^T \\ w_2 \cdot w_1^T & w_2 \cdot w_2^T \end{bmatrix} \times \begin{bmatrix} F_1 \\ F_2 \end{bmatrix} = \begin{bmatrix} w_1 \cdot w_1^T \\ w_2 \cdot w_2^T \end{bmatrix} \tag{8}$$

The subjective and objective comprehensive weight vector values were calculated after normalization of the coefficients.

$$F_h^* = \frac{|F_h|}{\sum_{h=1}^{2} |F_h|} \qquad w_3^T = F_1^* w_1^T + F_2^* w_2^T \tag{9}$$

F_h^* is the new coefficient after the normalized treatment.

3.3.Evaluation model based on TOPSIS improved by grey correlation

TOPSIS is an evaluation method that can solve the multi-attribute decision problem. By calculating the degree that the evaluation object is relatively close to the ideal solution as a comprehensive evaluation criterion, grey association analysis is introduced to quantify the degree of correlation between attributes, which can improve the accuracy and credibility of the decision results[22]. The specific calculation steps are performed as follows:

1) Standardized processing of the raw data: The initial evaluation moment is constructed from individual evaluation schemes and individual evaluation indicators $D = (d_{ij})_{m \times n}$, and the indicator were standardized to obtain the standardized evaluation matrix, get $Y = (y_{ij})_{m \times n}$,The positive indicators were standardized as follow:

$$y_{ij} = d_{ij} \Big/ \sqrt{\sum_{i=1}^{n} d_{ij}^2} \tag{10}$$

The data of the negative indicator is taken as reciprocal and standardized by formula (10). In the formula, d_{ij} is the i indicator value of the j scheme. $i = 1, 2, ..., m$, $j = 1, 2, 3, ..., n$.

2) The weights are determined by the BWM-CRITIC method: $w = \{w_1, w_2, ..., w_j, ..., w_n\}$. $0 \le w_j \le 1$ $\sum_{j=1}^{n} w_j = 1$. The standardized evaluation matrix $Y = (y_{ij})_{m \times n}$ was assigned after determining the weights, and calculate weighted evaluation matrix $K = (K_{ij})_{m \times n}$.

$$K_{ij} = w_j \times y_{ij} \tag{11}$$

3) Determine the positive ideal solution: $K^+ = \left\{K_1^+, K_2^+, \ldots, K_j^+, \ldots, K_n^+\right\}$, negative ideal solution $K^- = \left\{K_1^-, K_2^-, \ldots, K_j^-, \ldots, K_n^-\right\}$.

$$K_j^+ = \left\{ \max_{1\le i\le m} K_{ij} \mid j = P, \min_{1\le i\le m} K_{ij} \mid j = N \right\}$$
$$K_j^- = \left\{ \min_{1\le i\le m} K_{ij} \mid j = P, \max_{1\le i\le m} K_{ij} \mid j = N \right\} \tag{12}$$

K_j^+ represents the positive ideal solution of the j indicator, K_j^- represents the negative ideal solution of the j indicator. P represents positive indicator and N represents negative indicator.

4) Calculating the Euclidean distance between the positive and negative ideal solutions.

$$s_i^+ = \sqrt{\sum_{j=1}^{n} \left(K_{ij} - K_j^+ \right)^2}, i = 1, 2, \ldots, m$$
$$s_i^- = \sqrt{\sum_{j=1}^{n} \left(K_{ij} - K_j^- \right)^2}, i = 1, 2, \ldots, m \tag{13}$$

5) The TOPSIS method improved by grey association： The correlation between traditional TOPSIS indicators is linear and does not consider nonlinear relationships. The TOPSIS method improved by grey association could analyze the degree of association between indicators, which can more accurately reflect the nonlinear relationship between indicators. Use the comprehensive relative closeness replace the Euclidean distance measure to improve the grey correlation coefficient. The grey correlation coefficient was calculated as follow:

$$\xi_{ij}^+ = \frac{\left(\min_i \min_j \Delta_{ij}^+ + \rho \max_i \max_j \Delta_{ij}^+ \right)}{\left(\Delta_{ij}^+ + \rho \max_i \max_j \Delta_{ij}^+ \right)} \tag{14}$$

$$\xi_{ij}^- = \frac{\left(\min_i \min_j \Delta_{ij}^- + \rho \max_i \max_j \Delta_{ij}^- \right)}{\left(\Delta_{ij}^- + \rho \max_i \max_j \Delta_{ij}^- \right)} \tag{15}$$

ξ is the resolution coefficient, generally take 0.5[23]. Δ_{ij}^+ , Δ_{ij}^- are the absolute difference between the index data and the positive and negative ideal solution is calculated based on the weighted evaluation matrix.

6) Grey correlations were calculated and were dimensionless：

$$q_i^+ = \frac{1}{n} \sum_{j=1}^{n} \xi_{ij}^+, q_i^- = \frac{1}{n} \sum_{j=1}^{n} \xi_{ij}^- \tag{16}$$

$$S_i^+ = \frac{s_i^+}{\max_{1\le i\le m} s_i^+}, S_i^- = \frac{s_i^-}{\max_{1\le i\le m} s_i^-}$$
$$Q_i^+ = \frac{q_i^+}{\max_{1\le i\le m} q_i^+}, Q_i^- = \frac{q_i^-}{\max_{1\le i\le m} q_i^-} \tag{17}$$

7) The comprehensive distance of each evaluation scheme to the positive and negative ideal solution is calculated, and the relative closeness is determined：

$$L_i^+ = \alpha Q_i^+ + \beta S_i^-$$
$$L_i^- = \alpha Q_i^- + \beta S_i^+ \tag{18}$$

$$O_i = \frac{L_i^+}{L_i^+ + L_i^-} \tag{19}$$

α and β were taken as 0.5 [24].The relative closeness reflects the similarity difference between the scheme indicator and the ideal solution. According to the calculation results, the greater the relative closeness means that the better the scheme is.

4. Model validation with routes in Qinzhou Bay

In 2023, the Maritime Bureau of Qinzhou, Guangxi, People's Republic of China, issued a notice regarding the survey and construction operations of the offshore wind power demonstration project in Qinzhou. Due to the significant impact of constructing the offshore wind farm on the nearby planned routes and customary ship routes, adjustments should be made to the existing ship routes to ensure the safe navigation of vessels after the completion of the offshore wind power project. To ensure the safety of maritime traffic and enhance waterway efficiency, as well as to coordinate the development of offshore wind power construction, two alternative schemes have been designed.

In the context of the evaluation indicator system, data for indicators $C_{1\text{-}2}$, $C_{5\text{-}7}$, and $C_{11\text{-}14}$ have been sourced from multiple references, including the "Study on Navigational Safety Impact of the U Site Project" the "National General Plan for Coastal Ship Routes," "China Port Guide C103 " as well as updated nautical charts for the project area and publicly available information from maritime authorities. Qualitative indicators $C_{3\text{-}4}$ and $C_{8\text{-}10}$ were developed following the guidelines specified in the "Technical Guidelines for Navigational Safety Analysis in Offshore Wind Farm Site Selection". Surveys were designed based on these guidelines, and consultations were held with stakeholders, including users of Qinzhou Bay, offshore wind farm developers, and experts in the relevant domains. Following expert validation, the values for each indicator corresponding to the alternative plans were determined by assessing their conformity with the highest value. Taking all these factors into account, the evaluation indicator values for the two alternative plans can be found in Table 3.

Table 3 Index value of each scheme

indicators	**Scheme1**	**Scheme2**
The closest distance between the route to the wind farm C_1	1.52	2.00
Ratio of submarine cable length to wind farm width C_2	1.51	1.02
Disturbing of wind farms on ship communication and navigation equipment in the routes C_3	4.31	3.21
The influence of the wind farm on the ship lookout in the routes C_4	3.12	2.21
The coverage degree of the existing traffic flow trajectory C_5	58	62
Maximum steering Angle C_6	45	75
Ratio of the route width to the maximum captain C_7	0.121	0.122
The degree of conflict between route and anchorage or other special navigable waters C_8	0.311	0.341

the index describe the wind pushes away C_9	0.521	0.501
the index describe the flow pushes away C_{10}	0.261	0.311
The ratio of aquaculture cleaning area to route area C_{11}	0.721	0.592
The ratio of survey area for water depth to route area C_{12}	0.121	0.091
Coverage degree of VTS C_{13}	5.2	4.1
Coverage degree of aids to navigation C_{14}	18.2	19.1

4.1.Determination of indicator weight

In this study, a combination of expert opinions was utilized. The subjective weights for the criterion and indicator layers were determined using the Best-Worst Method (BWM). Subsequently, the objective weights for the indicator layer were established through the CRITIC method. Finally, the optimal weights were determined using the Game Combination Weighting Method by matlab. The results of the indicator weight calculations can be found in Table 4.

Table 4 Combined weight of index of evaluation of routes in Qinzhou Bay

standard layer	**standard layer weight**	**Indicator layer**	**Indicator layer subjective weight**	**Indicator layer objective weight**	**combination weight**
B_1	0.4323335560949030	C_1	0.496644295302013	0.0691	0.208392648
		C_2	0.0671160939597315	0.0749	0.030971745
		C_3	0.164486644295302	0.0645	0.085115904
		C_4	0.271734966442953	0.0683	0.101284478
B_2	0.2421234571177500	C_5	0.271954887218045	0.0744	0.068454784
		C_6	0.0451127819548872	0.0823	0.013911566
		C_7	0.484952406015038	0.0775	0.115985534
		C_8	0.187686992481203	0.0709	0.046771145
B_3	0.1212234342588700	C_9	0.427272727272727	0.0729	0.05276899
		C_{10}	0.563727272727273	0.0697	0.069419865
B_4	0.1616871704745160	C_{11}	0.753446753246753	0.0638	0.119350645
		C_{12}	0.246753246753247	0.0722	0.041236994
B_5	0.0426323820539611	C_{13}	0.572727272727273	0.0718	0.026154062
		C_{14}	0.427272727272727	0.0677	0.02019164

4.2.Evaluation result

The first step is to standardize the raw data and create a standardized evaluation matrix Y. Next, calculated the weighted evaluation matrix K based on the combination weights determined in the previous section. Then, using Formula (13), establishing the positive and negative ideal solutions. Applying the Grey Relational Analysis method to compute the comprehensive relative closeness as the holistic evaluation level for each alternative, as shown in Table 5.

Table 5 Relative similarity to the ideal scheme

Scheme	**Positive ideal solution correlation degree**	**Positive ideal solution correlation degree**	**Improved comprehensive relative closeness degree**	**order**
Scheme1	0.776998088	0.7865	0.484735467889501	1
Scheme2	0.819819105	0.7777	0.530692515547091	2

From the rankings in Table V, it is evident that among the two alternatives, Scheme 2 is closest to the positive ideal solution, and is Same as actual results.

5. Conclusion

1) This paper, based on research conducted both domestically and internationally concerning the evaluation of port waterway routes and the impact of offshore wind farms on vessel navigation, follows the principles of systematicity, specificity, scientific rigor, and operational feasibility. It establishes a primary evaluation indicator system, comprising factors related to the navigational impact of offshore wind farms, route considerations, hydro-meteorological conditions, economic factors, and organi-zational management. This system consists of 14 secondary indicators for the assessment of inbound and outbound port navigation routes under the influence of offshore wind farms.

2) This paper have employed a combined weighting method, the BWM-CRITIC approach, along with an enhanced TOPSIS method using grey relational analysis to construct a comprehensive route selection evaluation model. This model is applied to evaluate inbound and outbound port route schemes under the influence of offshore wind farms. It effectively reduces the subjectivity and uncertainty in the evaluation process, enhances the traditional TOPSIS approach, and provides a more precise representation of the interrelationships between evaluation criteria. Consequently, it enhances the credibility of the evaluation results

3) Using Qinzhou Bay as a case study, this paper conducted a practical validation of the evaluation model, and performed a comprehensive evaluation of two route schemes and determined that the second scheme was the optimal choice. The evaluation results were consistent with the actual project outcomes. The case analysis demonstrates the strong applicability of this evaluation model in assessing routes under the influence of offshore wind farms. It also offers valuable insights for optimal vessel route selection.

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