Comprehensive Assessment Model for Navigation Safety Risks in Area of Offshore Wind Farm

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Abstract: To address the challenge of assessing regional system safety risks in the context of the large-scale, clustered development of offshore wind farm regions, this study focuses on China's coastal offshore wind farm regions and constructs a comprehensive safety risk assessment model for offshore wind farm regions based on multi-spatio-temporal coupling. In this model, we first identify risk factors in offshore wind farm regions from a four-dimensional perspective encompassing people, machinery, environment, and management, and introduce a multi-spatio-temporal coupling factor to optimize the indicator system. Next, we use the Analytic Hierarchy Process (AHP) to determine the weighting of each assessment indicator, and then combine this with the Fuzzy Comprehensive Evaluation Method to establish a comprehensive safety risk assessment model for offshore wind farm regions regions. Finally, we apply this model to the risk assessment of a real coastal wind power region. The results indicate that, at the present time, the overall risk level of a specific offshore wind farm regions area is classified as "moderate risk." This assessment model can effectively quantify the dynamic coupled risks in offshore wind farm regions areas, providing a theoretical basis and technical support for the planning, layout, and safety supervision of offshore wind farms.

Keywords: Offshore Wind Farm; Navigation Safety; Fuzzy Comprehensive Evaluation Method; Risk Evaluation

1. Introduction

Against the backdrop of the ongoing advancement of the "dual carbon" goals and the strategy to build a maritime power, coastal wind power generation has become a key focus of clean energy development in China's coastal regions. Currently, as the siting of offshore wind farms shifts from single-site development toward large-scale, clustered development and full-lifecycle operations, safety issues have evolved from risks associated with individual facility failures or single operational phases to regional systemic risks involving the combined effects of multiple factors, including navigation environments, offshore construction, operation and maintenance activities, facility and equipment conditions, and organizational management. Particularly in scenarios where multiple wind farms coexist and construction and operational phases overlap, the risks in offshore wind energy areas may exhibit greater dynamism, coupling, and diffusion [1]. Therefore, developing comprehensive assessment models that reflect the overall characteristics of the region and the dynamic evolution of risks has

become a critical issue in offshore wind energy safety management research.

Scholars both domestically and internationally have conducted research on safety risks associated with offshore wind farm regions from various perspectives, primarily covering navigation risks during construction and operation and maintenance (O&M) phases, risks related to turbine structures and facilities, specific disaster risks in wind farms, and wind farm planning and decision-making. Regarding navigation safety, Yu et al. systematically reviewed the current state of research on the quantification of vessel navigation risks in offshore wind farm regions waters [2]. Li et al. proposed a path planning method for O&M vessels in offshore wind farms based on an improved A* algorithm [3]. This method overcomes the limitations of the traditional A* algorithm, which fails to account for dynamic obstacles, water currents, and crossing channels during path planning for O&M vessels in offshore wind farms, resulting in significant improvements in path smoothness and the overall risk value of the planned path. Wang et al. established an evaluation index system for navigation safety in offshore wind farm construction waters [4]. The results indicate that offshore wind farm construction has a significant impact on the navigation environment and traffic order in adjacent waters. Teng et al. proposed a comprehensive assessment method for the safety distance between vessels and offshore wind farms based on AIS data to reduce navigation risks for vessels near wind farm waters [5]. Wang et al. combined fuzzy AHP-DEMATEL with a cloud model to study the navigation safety assessment of offshore wind farms; this method effectively enhances the systematic nature of indicator weight identification and risk determination [6]. Zhang et al. constructed a multi-objective optimization model to assess vessel navigation risks in offshore wind farm areas, expanding the application of risk assessment in front-end planning [7]. Some international scholars have studied the impact of offshore wind farm regions development on maritime traffic safety. Rutkowski et al. utilized a spatial vessel domain model to investigate navigation risks near proposed wind farms [8]. Son et al. conducted research on the design of navigation channel widths adjacent to offshore wind farms based on AIS data and collision probability models, arguing that wind farm development requires a comprehensive consideration of collision risks between vessels as well as between vessels and wind turbines [9]. Milin et al. pointed out through extensive literature analysis that offshore wind farms may increase the complexity of maritime traffic, which may lead to navigation safety and collision accidents [10].

In terms of wind farm construction, operation and maintenance, and facility safety. Huang Hui et al. used the AHP fuzzy comprehensive evaluation method to quantitatively analyze the safety risks of construction and hoisting operations in offshore wind farms, and verified the applicability of the fuzzy evaluation method in high-risk operation scenarios. Dong et al. constructed a safety risk model for offshore wind turbine installation operations based on the AHP-fuzzy comprehensive evaluation method, covering five dimensions—personnel, management, equipment, vessels, and electrical systems—to achieve a comprehensive assessment of safety risks during installation [11]. Zhu et al. proposed an FAHP-based evaluation method to address lightning disaster risks during the operational phase of offshore wind farms [12]. In addition, some researchers have conducted studies from the perspectives of the full life cycle and systems engineering. Huang et al. identified multi-level risk factors and employed AHP and the risk matrix method to conduct safety evaluation research during the construction of offshore wind farm regions subsea cables [13]. Kim et al. developed an HSE risk assessment module for offshore wind farm regions based on systems engineering methods, using a combination of risk assessment methods to address risks under conditions of uncertainty [14].

Based on this, this paper identifies risk factors from four dimensions—human, machine, environment, and management—across the entire lifecycle of offshore wind farm regions areas. It further introduces time-coupled and space-coupled factors under multi-spatio-temporal coupling. Finally, by combining the Analytic Hierarchy Process (AHP) with the Fuzzy Comprehensive Evaluation Method, the paper constructs a comprehensive dynamic assessment model for offshore wind farm regions safety risks. Through a risk assessment of a specific offshore wind farm regions area along China's coastline, the research findings provide a theoretical basis for the planning and layout of offshore wind farms, the assurance of navigation safety, and safety supervision.

2. Identification of Regional Risk Factors for offshore wind farm regions

Unlike the risks associated with a single wind farm, the regional risk assessment of offshore wind farms is a complex system comprising wind farms at various stages of development and in different water areas. It should be treated as a dynamic,

integrated whole, necessitating a comprehensive analysis; this also presents greater challenges for identifying and mitigating water-related risk factors.

This paper treats offshore wind farms within the entire lifecycle of an offshore wind farm regions area as a single entity, identifies their primary risk factors, and then conducts a risk assessment of the offshore wind farm regions area based on these identified risk factors. By analyzing risk factors from four perspectives—human, machinery, environment, and management—the risk factors for offshore wind farm regions areas are summarized as follows: environmental factors (natural environment and transportation environment), human factors (crew and operational personnel), management factors (corporate management and management by supervisory authorities), and machinery factors (vessel-related and equipment-related). The risk factors for offshore wind farm regions areas are presented in Table 1.

Table 1. Identification of key risk factors in offshore wind farm regions areas

| Risk Type		Key risk factors
Environmental factors	Natural environment	Wind, waves, and currents (typhoon)
		Heavy fog
		Thunder and lightning
		Sensitive resources nearby
		Natural Conditions of the Project Site
	Transportation Environment	Insufficient water depth in the channel
		Intersection of customary routes and existing routes
		There are many vessels operating in the wind farm area
		Traffic chaos
		Lack of navigation aids
Human factors	Crew members	Insufficient crew training
		Crew members' violations
		Unfitness of crew members
		Lack of safety awareness
	Operators	Operators lack sufficient skill
		Operators' non-compliance with operating procedures
		Other safety hazards
Management factors	Business Management	Management negligence at the enterprise level
		Inadequate emergency response plans/safety operating procedures
		Unnecessary warning and monitoring equipment
		Inadequate corporate communication systems
	Management and Supervision of Administrative Units	Inadequate supervision or guidance from regulatory authorities
		Lack of clarity regarding the responsibilities of supervisory agencies
		Poor communication between regulatory agencies and businesses
Machine factors	In terms of ships	A collision caused by a loss of control of an individual vessel
		The ship's emergency lifesaving equipment is inadequate
		Fire and Explosion Accidents
		Personal protective equipment is incomplete or in poor condition
	In terms of equipment	Inadequate safety equipment at wind farms
		Failure or malfunction of wind turbine structures and equipment components

Given that offshore wind farm regions zones contain wind farms at various stages of development, and that these wind farms interact with one another both temporally and spatially, analysis cannot rely solely on initially identified indicators. Instead, it is necessary to conduct a more in-depth exploration of the inter-wind-farm indicator data. Therefore, risk factors under multi-spatio-temporal coupling must be identified to form coupled factors, and the risk factors listed in Table 1 must be adjusted accordingly.

3. Development of an Indicator System for Assessing Wind Power Safety Risks in Coastal Areas

A scientifically reasonable evaluation index system is an important prerequisite for conducting safety risk assessments in offshore wind power regions. The Analytic Hierarchy Process (AHP) is highly applicable to complex systems involving multiple objectives and criteria. It can decompose complex risk issues into several interrelated components and establish a hierarchical structure based on the dominance relationships among these factors, thereby laying the foundation for subsequent weight determination and comprehensive evaluation. For offshore wind farm regions regions, using the AHP to construct an indicator system helps achieve a systematic characterization of regional safety risks.

Offshore wind farm areas face a variety of uncertainties that vary over time and space; moreover, these uncertainties may interact with one another, posing greater challenges for the identification and mitigation of offshore risks. Therefore, it is necessary to apply coupling theory to integrate the spatiotemporal aspects of offshore wind farms throughout their entire lifecycle in order to identify risk factors. As shown in Figure 1, a three-tiered hierarchical evaluation index system has been established, comprising the objective layer, the criterion layer, and the indicator layer. The objective layer defines the ultimate purpose of the evaluation; the criterion layer classifies risk types across four dimensions; and the indicator layer breaks these down into multiple specific, measurable risk indicators, thereby forming a comprehensive risk evaluation index system. The criterion layer serves as a bridge connecting the objective layer and the indicator layer, playing a pivotal role in the index system.

Figure 1. Identification of Major Risk Factors in offshore wind farm regions Areas
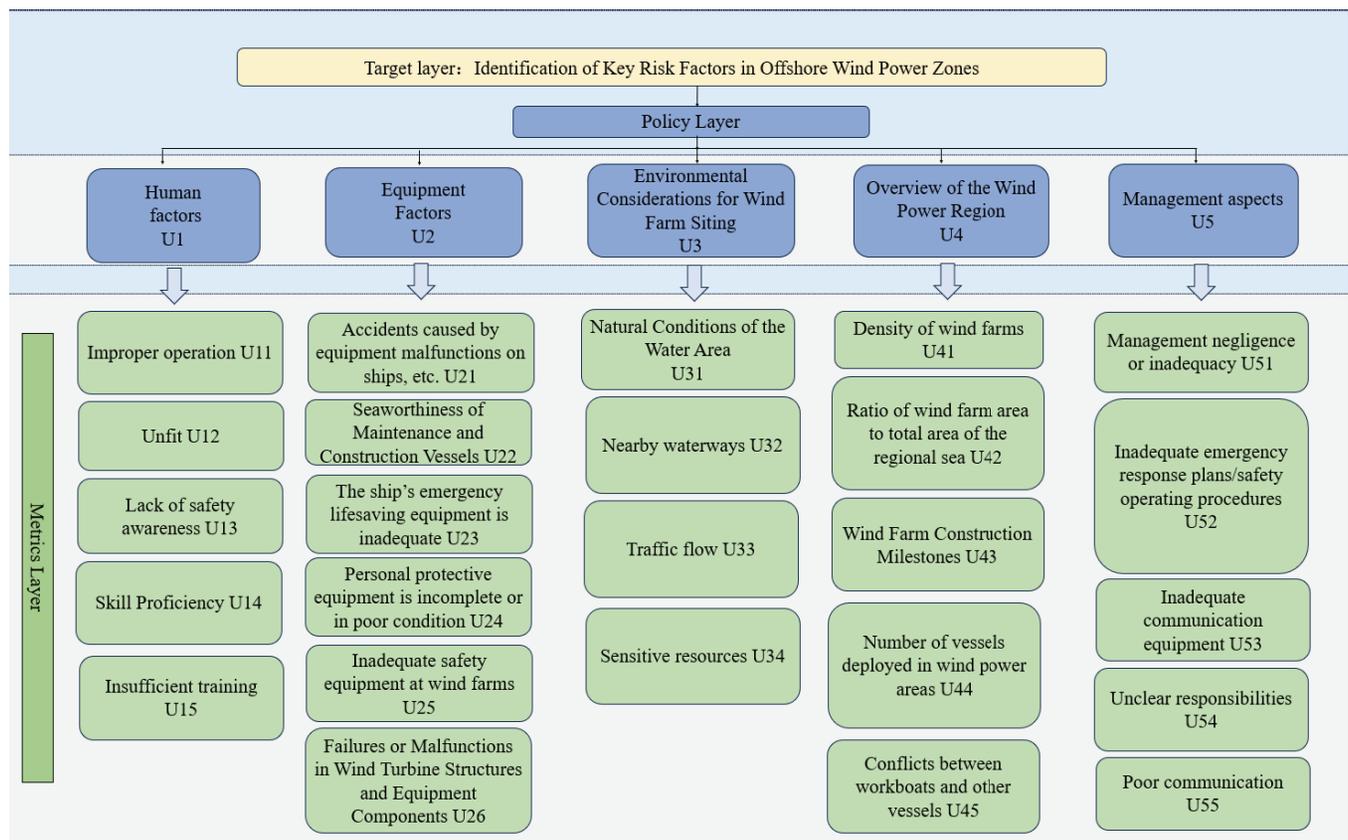
Specifically, the human factor includes personnel involved in safety within the wind farm area, such as construction workers, operational staff, and managers. The probability of non-compliant operations refers to the likelihood of personnel in the wind

farm area engaging in non-compliant operations, quantified as a value between 0 and 1; a higher value indicates a greater probability of non-compliant operations and a higher risk.

With regard to equipment-related factors, accidents caused by vessel equipment failures refer to factors that may lead to risks due to malfunctions in the vessel's own facilities and equipment; these are quantified on a scale of 0 to 1, with higher values indicating greater risk. Failures or malfunctions in wind turbine structures and components reflect the reliability or failure rate of wind turbine facilities and equipment in the wind power area; these are quantified on a scale of 0 to 1, with higher values indicating higher risk.

Regarding environmental factors for wind farm siting, the natural conditions of the water area include natural factors such as typhoons, waves, and currents, quantified on a scale of 0 to 1; nearby shipping lanes refer to the conditions of shipping lanes near the wind farm, quantified on a scale of 0 to 1; and traffic flow refers to traffic conditions near the wind farm, quantified on a scale of 0 to 1.

Regarding the general characteristics of wind power areas, the distribution density of wind farms primarily reflects the degree of concentration of wind farms. It is generally believed that the higher the distribution density, the greater the risk. This is quantified on a scale of 0 to 1, with higher values indicating greater risk; Conflicts involving construction and O&M vessel traffic primarily consider the intersection of navigation routes among operational vessels. It is generally believed that the more intersections there are in the wind power area, the greater the potential risk. This is quantified as a value between 0 and 1, with higher values indicating greater risk.

With regard to management factors, management negligence or inadequacy refers to the failure of managers to adequately oversee wind farms and personnel in the wind power area. It is generally believed that the greater the negligence, the higher the risk of accidents or emergencies. This is quantified on a scale of 0 to 1, with higher values indicating greater risk. Poor communication refers to the level of information flow within the wind power area and is quantified on a scale of 0 to 1, with higher values indicating greater risk.

4. Comprehensive Dynamic Assessment Model for Wind Power Safety Risks in Coastal Areas

4.1 Determining Indicator Weights Using the Analytic Hierarchy Process

The weights for the regional risk assessment indicators of offshore wind farms were calculated using the Analytic Hierarchy Process (AHP). The specific calculation process is as follows:

(1) Construction of the Evaluation Matrix

Invite experts to assign importance scores to indicators, thereby constructing an evaluation matrix $X = \{X_1, X_2, ..., X_n\}$, as shown in Equation (1):

$$X = \begin{bmatrix} x_{11} & x_{12} & ... & x_{1n} \\ x_{21} & x_{22} & ... & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & ... & x_{mn} \end{bmatrix}$$

Where: x_{mn} represents the score assigned by expert n to indicator m.

(2) Calculation of combined weighted vector values

By combining the effects of different indicators, we obtain the combined weighted vector λ_{j+1} , as shown in the following equation:

$$\lambda_{j+1} = \frac{C_{n-1}^j}{\sum_{k=0}^{n-1} C_{n-1}^k} = \frac{C_{n-1}^j}{2^{n-1}}$$

Where: $\sum_{j=0}^{n-1} \lambda_{j+1} = 1$; C_{n-1}^j is the number of permutations of j elements selected from n-1 elements.

(3) Calculation of absolute weights.

Based on the weighted vectors, calculate the absolute weight w_i of indicator i, as shown in the following equation:

$$w_i = \sum_{j=0}^{n-1} \lambda_{j+1} \cdot X_j (j = 0,1, ..., n-1; i = 1,2, ..., m)$$

Where: X_j denotes the set of all indicator score vectors for expert j.

(4) Determination of relative weights

Based on the absolute weight of indicator i, calculate the relative weight σ_i of indicator i, as shown in the following equation:

$$\sigma_i = \frac{w_i}{\sum_{i=1}^{m} w_i}$$

4.2 A Dynamic Comprehensive Risk Assessment Method Based on Fuzzy Comprehensive Evaluation

Using the indicator weights determined by the Analytic Hierarchy Process (AHP), we developed a comprehensive regional risk assessment model for offshore wind farms based on the Fuzzy Comprehensive Evaluation Method.

(1) Determine the set of factors

The set of factors influencing the safety assessment of offshore wind farm regions under multi-temporal and spatial coupling can be represented by primary and secondary indicators as follows:

Level 1 indicator：$U=\{U_1,U_2,U_3,U_4,U_5\}$

Level 2 indicator：$U1=\{U_{11},U_{12},U_{13},U_{14},U_{15}\}$, $U2=\{U21,U22,U23,U24,U25,U26\}$, $U3=\{U_{31},U_{32},U_{33}\}$, $U4=\{U41, U42, U43,U44,U45\}$, $U5=\{U51,U52,U53,U54,U55\}$

(2) Determine the weight set

The weights of the indicators were calculated and determined using the Analytic Hierarchy Process described in Section 3.1.

(3) Create a collection of comments

The safety risks of offshore wind farm regions areas are classified into four levels: I, II, III, and IV, and are grouped into Rating Category V. The safety risk assessment ratings and their descriptions for offshore wind farm regions areas are shown in Table 2, and the classification criteria for safety risks in offshore wind farm regions areas are shown in Table 3.

Table 2. Safety Risk Classification Comments and Descriptions for offshore wind farm regions Zones

Comments	Risk Profile	Risk Description
I	Low risk	The risk is acceptable; no action is required.
II	General risks	Where risks are tolerable and cost-effective, efforts should be made to further mitigate them.
III	Significant risk	Where technically and economically feasible, risks must be mitigated
IV	High risk	This is extremely dangerous; immediate corrective action is required.

Table 3. Safety Risk Classification Standards for offshore wind farm regions Areas

Evaluation Criteria	[50,70]	[70,80]	[80,90]	[90,100]
Safety Risk Classification for offshore wind farm regions Zones	I	II	III	IV

(4) Determine the membership function

This method, which derives indicator scores based on actual scores or expert ratings, does not account for the ambiguity of boundaries between grades. When applying the fuzzy comprehensive evaluation method, membership degrees are primarily determined using membership functions. This allows for the consideration of transitional states between grades, thereby resolving the issue of fuzzy boundaries between grades. Therefore, selecting the trigonometric method to calculate the membership degree of evaluation indicators within evaluation grades can eliminate the unreasonable phenomena caused by abrupt changes between adjacent grade regions. The membership function formula is as follows:
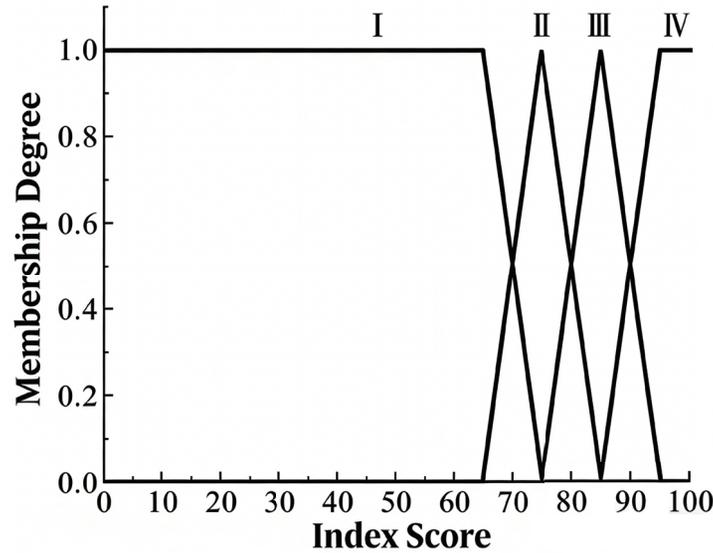
$$Y_{\mathrm{I}}(x) = \begin{cases} 1, 50 \leq x < 65 \\ \dfrac{75 - x}{10}, 65 \leq x < 75 \end{cases}$$

$$Y_{\mathrm{II}}(x) = \begin{cases} \dfrac{x - 65}{10}, 65 \leq x < 75 \\ \dfrac{85 - x}{10}, 75 \leq x < 85 \end{cases}$$

$$Y_{\text{III}}(x) = \begin{cases} \dfrac{x-75}{10}, 75 \le x < 85 \\ \dfrac{95-x}{10}, 85 \le x < 95 \end{cases}$$

$$Y_{\text{IV}}(x) = \begin{cases} \dfrac{x-85}{10}, 85 \le x < 95 \\ 1,95 \le x \le 100 \end{cases}$$

Figure 2 Triangular membership function

(5) Determine the fuzzy evaluation matrix

Construct the fuzzy evaluation matrix R_1、R_2、R_3、R_4. R represents a mapping from U to V defined by the fuzzy evaluation matrix, which can be expressed in matrix form as: $R=\{r_{jj}\}$, where $i=1,2,…,n$; $j=1,2,…,n.r_{ij}$. represents the membership degree of each single factor U_i for evaluation level V_j.

(6) Determine the comprehensive evaluation score and risk level

First, the fuzzy comprehensive evaluation set B for the factor set U is calculated based on the $B=W*R$ fuzzy comprehensive evaluation criteria. Next, the fuzzy comprehensive evaluation vectors for the first-level indicators are calculated sequentially to obtain the fuzzy comprehensive evaluation vector for the evaluation target. Finally, the fuzzy comprehensive evaluation score is calculated using the $S=B*G$ formula to determine the comprehensive evaluation grade for offshore wind farm regions.

5. Case Study

At present, there are multiple existing and under construction wind farms in a certain offshore wind farm area along the coast of China, based on the distribution map of wind farms and research data of wind farm areas. Adopting the constructed fuzzy comprehensive evaluation method to evaluate wind farms in offshore wind farm regions.

(1) Indicator weights derived from the Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP) was used to determine the weights for the fuzzy comprehensive evaluation of offshore wind farms under multi-spatiotemporal coupling; the weight values are shown in Table 4.

Table 4. Weighting Values for offshore wind farm regions Regional Indicators

Evaluation criteria	Weight allocation	Evaluation Criteria	Weight allocation
		Improper operation U11	0.0557
		Unfit U12	0.0655
Human factors U1	0.2360	Lack of safety awareness U13	0.0379
		Skill Proficiency U14	0.0464
		Insufficient training U15	0.0304

Evaluation criteria	Weight allocation	Evaluation Criteria	Weight allocation
		Accidents caused by equipment malfunctions on ships, etc. U21	0.0276
		Seaworthiness of Maintenance and Construction Vessels U22	0.0232
Equipment Factors U2	0.1288	The ship's emergency lifesaving equipment is inadequate U23	0.0112
		Personal protective equipment is incomplete or in poor condition U24	0.0195
		Inadequate safety equipment at wind farms U25	0.0311
		Failures or Malfunctions in Wind Turbine Structures and Equipment Components U26	0.0161
Environmental Considerations for Wind Farm Siting U3	0.1968	Natural Conditions of the Water Area U31	0.0534
		Nearby waterways U32	0.0444
		Traffic flow U33	0.0628
		Sensitive resources U34	0.0362
Overview of the Wind Power Region U4	0.2776	Density of wind farms U41	0.0358
		Ratio of wind farm area to total area of the regional sea U42	0.0446
		Wind Farm Construction Milestones U43	0.0771
		Number of vessels deployed in wind power areas U44	0.0546
		Conflicts between workboats and other vessels U45	0.0655
Management aspects U5	0.1608	Management negligence or inadequacyU51	0.0446
		Inadequate emergency response plans/safety operating procedures U52	0.0379
		Inadequate communication equipment U53	0.0207
		Unclear responsibilities U54	0.0316
		Poor communication U55	0.0259

(2) Comprehensive Risk Assessment Based on the Fuzzy Comprehensive Evaluation Method

Taking Wind Farm No. 19 as an example, the fuzzy comprehensive evaluation vector for the evaluation objective is calculated based on the $B = W * R$ fuzzy comprehensive evaluation criteria:

$$B = W * R = (0.2360, 0.1288, 0.1968, 0.2776, 0.1608) * \begin{bmatrix} 0 & 0.2892857 & 0.455426 & 0.2553412 \\ 0 & 0.2511250 & 0.414914 & 0.3333951 \\ 0.027134 & 0.1361788 & 0.508943 & 0.3277439 \\ 0.019668 & 0.2503604 & 0.500576 & 0.2293951 \\ 0.019664 & 0.1464842 & 0.4263845 & 0.3913503 \end{bmatrix}$$

$$= (0.01396178, 0.22047102, 0.46860397, 0.29431102)$$

Calculate the $S = B * G$ fuzzy comprehensive evaluation score using the formula:

$$S = B * G = \begin{pmatrix} 0.01396178 \\ 0.22047102 \\ 0.46860397 \\ 0.29431102 \end{pmatrix} * \begin{vmatrix} 100 \\ 85 \\ 75 \\ 60 \end{vmatrix} = 72.9$$

The final risk assessment result was 72.94. According to Tables 2 and 3, the comprehensive risk rating for Wind Farm No. 19 is Level II, which corresponds to "general risk"—meaning the risk is tolerable. However, if it is cost-effective to do so,

further risk mitigation measures should be implemented.

(3) Risk Assessment of Offshore Wind Farms

Based on collected data, field surveys, and consultations with wind power professionals, and taking into account risk factors, the wind farms in the study area were evaluated using assessment criteria across four dimensions: people, vessels, the environment, and management. The individual wind farms are shown in Figure 3.

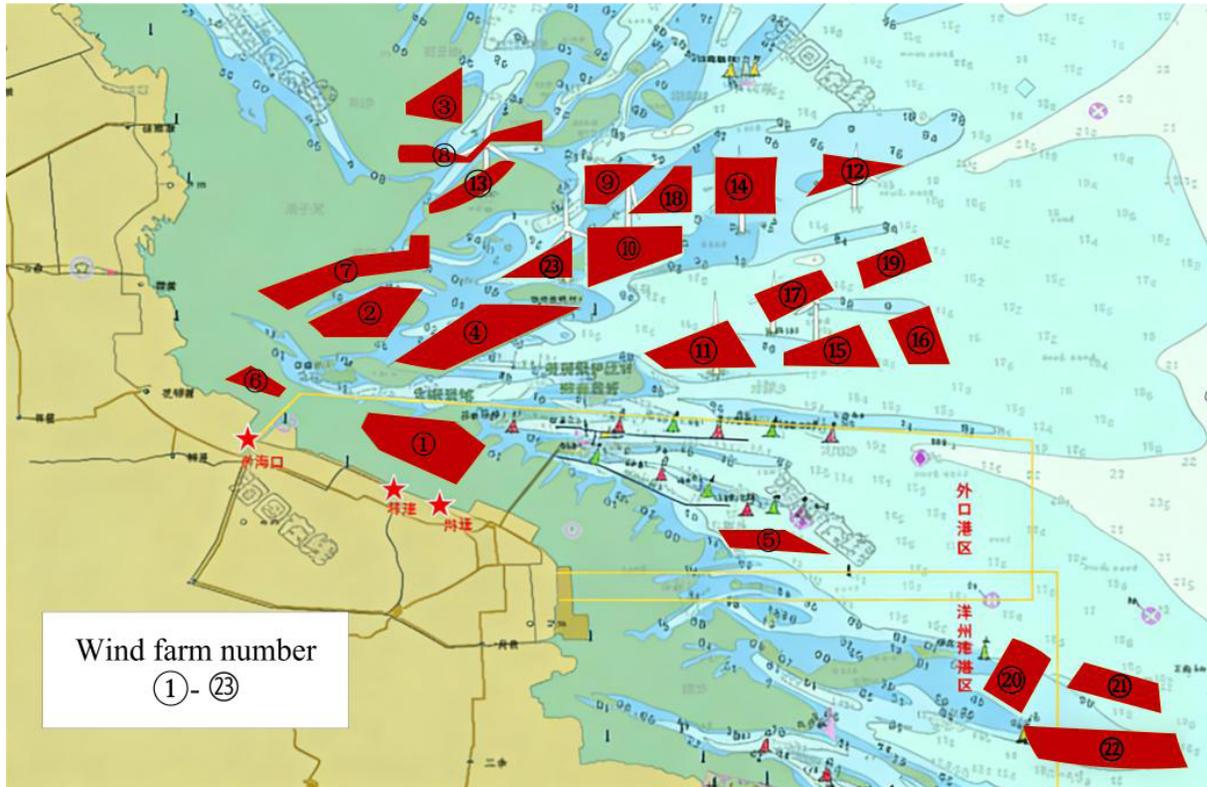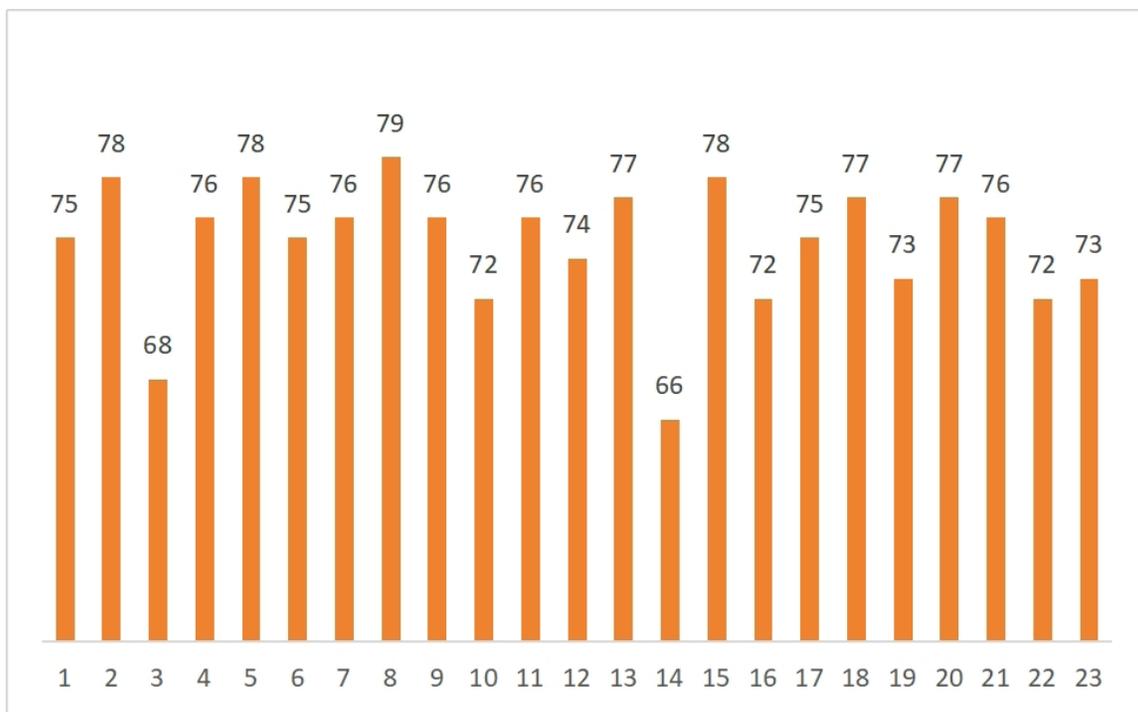*Figure 3. Map of Wind Farm Locations and Risk Assessment*

Figure 4. Distribution of Risk Assessment Values for Each Wind Farm

Based on the evaluation method described above, the final risk assessment ratings for each wind farm were determined, as shown in Table 3.

Table 5. Risk Assessment Results for Wind Farms in the Offshore Wind Farm Area

Number	Rating Level	Number	Rating Level
1	General risks	13	General risks
2	General risks	14	Low risk
3	Low risk	15	General risks
4	General risks	16	General risks
5	General risks	17	General risks
6	General risks	18	General risks
7	General risks	19	General risks
8	General risks	20	General risks
9	General risks	21	General risks
10	General risks	22	General risks
11	General risks	23	General risks
12	General risks		

An assessment of safety risks at 23 wind farms in the jurisdiction—covering both operational and construction phases—revealed that wind farms numbered 3 and 14 were classified as "low risk," while the remaining 21 wind farms were classified as "moderate risk." Although the overall risk level for the wind farm area is "moderate," several wind farms are currently in the construction phase and may be significantly affected by construction vessels. Therefore, for wind farms with higher risk assessment values and those in the construction phase, wind power companies and relevant departments should pay special attention to risk safety management and prevention measures for these facilities, further reducing risks during this stage and preventing the risk level from escalating further.

6. Conclusion

This paper conducts a systematic risk assessment analysis of a specific offshore wind farm in a coastal region of China. Risk factors were identified based on multi-spatio-temporal interactions, and an indicator system for evaluating wind power safety risks in coastal areas was established. Finally, a comprehensive risk assessment model for coastal wind power was constructed using the Analytic Hierarchy Process (AHP) and the Fuzzy Comprehensive Evaluation Method. Case analysis indicates that the overall risk level of wind farms under construction and in operation in the region during this period is "moderate." The application of the Fuzzy Comprehensive Evaluation Method to the risk assessment of a specific offshore wind farm in China's coastal region provides valuable theoretical references and practical applications for regional offshore wind farm regions safety management.

Funding

Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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