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The Impact of Offshore Wind Farm Construction on Maritime Traffic Complexity: An Empirical Analysis of the Yangtze River Estuary

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Abstract: The rapid growth of offshore wind farms (OWFs) as renewable energy sources has heightened concerns about maritime traffic safety and management in high-density traffic zones. These areas, characterized by complex interactions among diverse ship types and spatial constraints, require advanced situational awareness to prevent collisions and ensure efficient operations. Traditional maritime traffic systems often lack the granularity to assess the multifaceted risks around OWFs. Existing research has explored local traffic patterns and collision risks but lacks comprehensive frameworks for evaluating traffic complexity at both micro and macro levels. This study proposes a new complexity assessment model tailored to OWF areas, integrating micro-level ship interactions and macro-level traffic flow conditions to capture a holistic view of traffic dynamics. Using extensive historical AIS data from the Yangtze River Estuary, the model evaluates the impact of the proposed OWF on existing traffic complexity. The results demonstrate that OWFs increase navigational complexity, particularly in route congestion, course adjustments, and encounter rates between ships. Different ship types and sizes were also found to experience varying levels of impact, with larger ships and tankers facing greater challenges. By providing a quantitative framework for assessing traffic complexity, this research advances the field's ability to understand and manage the risks associated with OWFs. The findings offer actionable insights for maritime authorities and OWF operators, supporting more effective traffic management strategies that prioritize safety and operational efficiency in high-density maritime areas.

Keywords: traffic management; situation awareness; offshore wind farm; maritime traffic complexity

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1. Introduction

With the rapid expansion of offshore wind farms (OWFs) as critical sources of renewable energy, ensuring their safe and efficient operation has become a key concern [1,2]. OWFs are typically located in high-traffic maritime areas, where a diverse range of commercial ships, fishing boats, and recreational vessels coexist. This dynamic environment introduces significant challenges for maritime operators and OWF managers, especially in maintaining situational awareness (SA) to prevent collisions and operational disruptions. Effective situational awareness, which involves real-time perception of the surrounding environment, understanding of traffic dynamics, and projection of future risks, is essential for decision-making in these areas [3–5].

Maritime traffic complexity around OWFs is influenced by various factors, including different ship types, unpredictable weather, and spatial constraints imposed by OWFs [6,7]. Traditional maritime traffic management systems typically rely on radar and Automatic Identification System (AIS) data to track ship positions and movements [8,9]. However, these systems often fall short in addressing the unique complexities and risks of operations near OWFs [10]. Furthermore, the coexistence of OWF structures and dense maritime traffic necessitates advanced methods for risk assessment and management. Previous research has made progress in studying maritime safety and traffic flow near OWFs, but most studies focus primarily on local traffic patterns or collision risks. They often lack a broader, systemic perspective needed to measure traffic complexity at both micro and macro levels. The absence of a comprehensive framework capturing nuanced interactions between ships and OWFs across scales—from individual ship behaviors to broader traffic flow dynamics—has limited tools for accurately assessing traffic complexity in OWF areas. This gap limits predictive accuracy in understanding and mitigating risks posed by traffic complexity, especially under different environmental conditions and operational scenarios.

To address this gap, a novel maritime traffic complexity model is proposed to improve situational awareness in OWF areas. This model integrates micro-level interactions—both among ships and between ships and OWFs—and macro-level traffic conditions, providing a comprehensive understanding of traffic complexity. This system-level approach captures interactions among ship movements across scales and OWF spatial constraints, enabling more accurate risk assessments locally and globally.

This study focuses on the waters near the Yangtze River Estuary, where an OWF is planned. This region is characterized by high maritime traffic density and diverse ship types. In this area, ships navigate frequently, and the OWF's construction could significantly impact existing shipping lanes and ship passages. By analyzing and comparing extensive historical traffic data, this research aims to assess how the construction of the offshore OWF will affect traffic complexity in these waters and ensure safe ship passage after the OWF's construction. The findings will offer valuable data and support decision-making for maritime traffic management authorities and OWF operators, aiding in route optimization, traffic safety, and operational efficiency. This will help reduce ship collision risks while supporting sustainable development in the Yangtze River Estuary and the promotion of green energy.

The remainder of this paper is structured as follows: Section 2 reviews relevant research on maritime traffic safety in OWF areas. Section 3 outlines the proposed model and methodology. Section 4 presents the findings from actual maritime traffic data, and Section 5 discusses the findings and offers suggestions for future research.

2. Literature Review

Research consistently emphasizes that the presence of OWFs introduces additional risks for maritime traffic, primarily due to restricted navigable space and the close proximity of ships to wind turbines. Studies utilize fault tree analysis and statistical models to evaluate these risks, highlighting that ship collisions with turbines are more likely in high-traffic areas, particularly where adverse weather conditions exacerbate navigational difficulties [11–13]. AIS data are frequently used to monitor real-time ship movements and assess collision hotspots, offering predictive insights into areas where risks are heightened [14,15]. The combination of restricted sea room, weather impacts, and diverse ship types contributes to increased collision probabilities [16].

The spatial constraints imposed by OWFs significantly alter existing traffic flow, leading to rerouting and increased congestion in maritime areas. Studies indicate that OWFs reduce available navigable space, creating congestion points that heighten collision risks [17,18]. Changes affect not only commercial shipping routes but also fishing and recreational traffic, resulting in denser, more complex traffic environments [19,20]. Simulations and traffic models predict how OWFs impact ship behavior, suggesting that traffic densities and potential conflicts will increase, especially in regions with complex navigational patterns [21,22]. Additionally, the interaction between ship sizes and maneuverability in restricted areas complicates traffic dynamics [23].

Several studies focus on the increased navigational complexity in areas surrounding OWFs, which are often located in high-density maritime zones. Poor visibility, environmental conditions such as strong tides or high winds, and the complexity of ship encounters contribute to higher accident probabilities [24–26]. Research indicates that traditional maritime navigational aids may not suffice in these environments, necessitating enhanced navigational systems and increased deployment of surveillance technologies such as radar and real-time monitoring systems to reduce collision risks [27,28]. Additionally, inadequate marking of wind turbines and insufficient separation distances between OWFs and major shipping routes are identified as primary concerns affecting safe navigation [29,30].

To address safety concerns, advanced technologies like machine learning and enhanced Vessel Traffic Service (VTS) systems are increasingly being integrated into maritime safety strategies around OWFs. Machine learning models can process large datasets, such as AIS data, to predict ship behavior and identify potential conflict zones, enabling more proactive decision-making [31–33]. Enhanced VTS systems, which provide real-time data on ship positions and environmental conditions, are critical in managing traffic complexity near OWFs [34,35]. Regulatory measures, such as establishing exclusion zones and rerouting traffic, are recommended to reduce navigational hazards. Implementing these measures can significantly improve maritime safety, reduce congestion, and prevent accidents [36–39].

Despite the growing body of the literature examining maritime traffic safety in relation to OWFs, significant research gaps remain, particularly concerning the quantification of traffic complexity in these environments. While existing studies have largely focused on the risks of ship collisions and the implications of traffic flow changes due to the construction of OWFs, there is limited investigation into how these factors interact over time and the extent of their cumulative impacts on traffic complexity.

(i) Most prior research has primarily dealt with qualitative assessments of safety and risk management, often using anecdotal evidence or case studies without providing a comprehensive framework to quantitatively measure traffic complexity in OWF areas. The proposed research aims to fill this gap by developing specific metrics and models to quantify the complexity of maritime traffic in relation to OWFs before and after their construction.
(ii) While some studies have addressed the changes in navigational patterns and collision risks in areas surrounding OWFs, few have conducted thorough comparative analyses of traffic complexity levels before and after the establishment of OWFs. Most existing studies focus on local traffic patterns or immediate impacts, lacking a longitudinal perspective that could provide insights into how traffic dynamics evolve over time.
(iii) Although some studies have explored analytics in maritime safety, the integration of these technologies specifically to measure and analyze traffic complexity in the context of OWFs is under-researched. The proposed research could leverage these technologies to create models that assess how traffic complexity changes in relation to ship behaviors in OWF areas.

The complexity assessment method proposed in this paper for OWF areas and the contributions of this work are threefold:

(i) Unlike most previous studies that focus on qualitative assessments, this method develops specific quantitative metrics using actual data, allowing for an accurate measurement of traffic complexity in OWF areas. This advantage makes the research findings more scientific and objective, contributing to policy formulation and risk management.
(ii) This paper conducts a systematic comparative analysis of the impact of traffic complexity before and after the construction of OWFs, filling the gaps in the existing literature on this topic. Through comparison, it clearly reveals the specific effects of OWF construction on maritime traffic dynamics, providing strong empirical support.
(iii) In assessing traffic complexity, this paper comprehensively considers the interactions among ships as well as the interactions between ships and OWFs. This holistic approach will help to gain a deeper understanding of the collective influence of various

factors on traffic complexity, thereby enhancing the evaluation and management of operational risks.

The method presented in this paper not only addresses the shortcomings of current research but also offers new ideas and tools for future traffic safety management in OWF area, promoting further research and practice in this field.

3. Method

3.1. Research Area

The research area is the Yangtze River Estuary, one of the busiest maritime traffic corridors globally, marked by a high shipping density and complex traffic dynamics. The Yangtze River Estuary links the Yangtze River Basin with the East China Sea and serves as a critical intersection of China's inland waterways and international shipping routes. A diverse range of ships navigate these waters, including cargo ships, container ships, fishing boats, and passenger ships. The region also contains dense networks of shipping lanes, anchorages, and frequent fishing activities, further intensifying maritime traffic complexity. A plan to construct an OWF near the Yangtze River Estuary is currently part of China's green energy strategy. The Yangtze River Estuary has abundant wind resources, making it suitable for OWF development. According to the Shanghai 2024 offshore wind power project competitive allocation work plan (https://fgw.sh.gov.cn/fgw_ny/20240320/b12c958e447240989804e75351945baf.html, accessed on 3 December 2024), the proposed OWF areas are shown in Figure 1. However, the presence of OWF facilities and the resulting navigation route adjustments are expected to significantly impact local traffic complexity. Therefore, selecting the Yangtze River Estuary as the study area will effectively reflect the potential impact of OWF construction on traffic within a highly complex maritime environment.

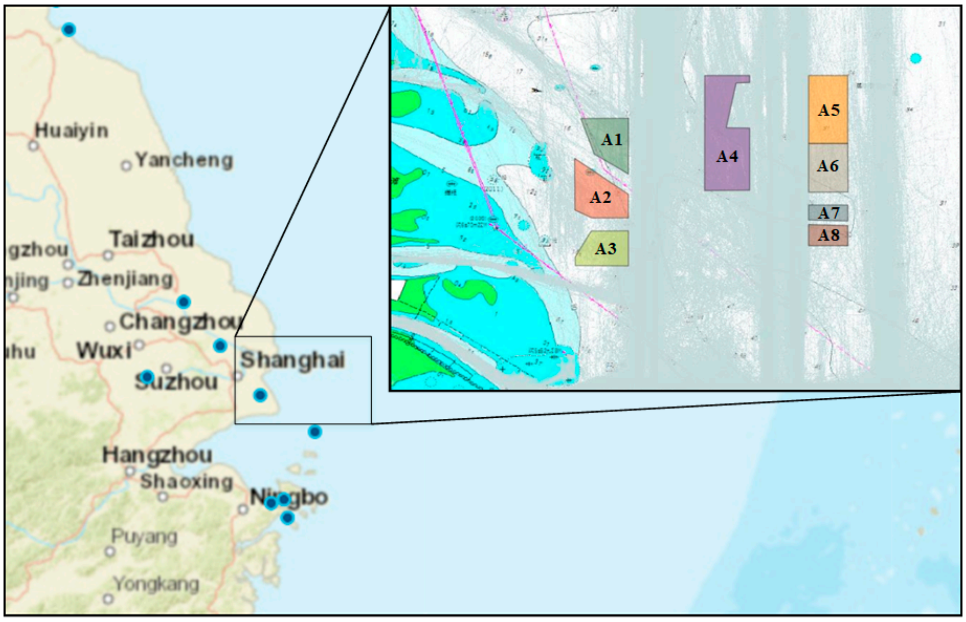

Figure 1. Research area and the proposed OWF areas.

To conduct a comprehensive analysis of traffic complexity, historical ship AIS data from the research area were used to validate the proposed method's effectiveness. The AIS data include latitude, longitude, speed, course, and ship type, offering detailed trajectories of ship movements in the area and reflecting traffic conditions before the OWF's construction. According to the SOLAS, all cargo ships above 300 tons engaged in international navigation, all cargo ships above 500 tons engaged in domestic navigation, and all passenger ships must be equipped with AIS equipment. AIS data are received in a series of messages at irregular time intervals, and errors are inevitable during data collection, transmission, and reception. Therefore, the data must undergo cleaning and interpolation to reduce the impact of errors. Additionally, since AIS data are sent at different times randomly, interpolation is needed to process the data.

First, the AIS data were cleaned by removing data with abnormal ship positions, speeds, and courses in the experimental dataset. After cleaning and filtering the AIS data, a linear interpolation algorithm with a 2 s interval was applied. Table 1 shows a sample of the preprocessed AIS data. Using this AIS data, this study developed a traffic complexity evaluation model to analyze the dynamic relationships among ships and between ships and the OWF. This study quantified the baseline traffic complexity before the OWF's construction by calculating complexity factors and then compared it with post-construction data to evaluate the impacts on navigational safety and traffic flow.

Table 1. Portion of preprocessed AIS data.

MMSI	Latitude	Longitude	Speed	Course
413342350	122.7509°	31.4386°	11.6 kn	169.9°
413361840	122.8218°	31.3933°	10 kn	4.5°
413702570	122.8139°	31.3952°	9.8 kn	355.9°
413705420	122.7197°	31.4539°	6.0 kn	166.2°
413275370	122.8043°	31.4577°	13.1 kn	17.6°
...	...	...	...	...
413256860	122.7545°	31.4473°	6.8 kn	170.4°

3.2. Complexity Measurement for Ship–Ship Relationship

3.2.1. Dynamic Traffic Density Factor

Traffic density is often used to evaluate the characteristics of waterway traffic flow. However, traditional methods fail to fully capture the spatial distribution and aggregation of ships. To achieve a more accurate analysis of traffic flow, the concept of dynamic density was introduced. This concept not only considers the number of ships but also incorporates their distribution and movement within a specific area, providing a better reflection of the dynamic changes in waterway traffic [40,41]. Suppose there are n ships in the area and that their positions can be expressed as: $\{(x_i, y_i)|i \in n\}$. In this section, the positions of ships are obtained by converting the latitude and longitude into Gauss coordinates, with the units in meters. The central position of these n ships can then be calculated as:

$$\vec{P} = \begin{bmatrix} \overline{X} \\ \overline{Y} \end{bmatrix} = \begin{bmatrix} \frac{1}{n}\sum_{i=1}^{n} x_i \\ \frac{1}{n}\sum_{i=1}^{n} y_i \end{bmatrix} \tag{1}$$

The distance from ship i to $\vec{P}$ is:

$$s_i = \sqrt{(x_i - \overline{X})^2 + (y_i - \overline{Y})^2} \tag{2}$$

Therefore, an exponential function can be constructed to reflect the nonlinear relationship between ship aggregation and complexity.

$$C_{den}^{i} = e^{-\lambda s_i} \tag{3}$$

where λ represents the weight of the distance. As the distance decreases, the complexity increases nonlinearly.

The λ reflects the sensitivity of maritime supervision to changes in the distance between ships. A greater distance weight indicates a higher sensitivity to the variation in ship-to-ship distance, emphasizing the impact of the distance on the dynamic density.

Suppose there is only one ship in a given region; the dynamic density at that moment is 1. When another ship gradually enters the region from a distant location, the change in the dynamic density is minimal and can almost be ignored. Therefore, under such circumstances, the dynamic density of the region remains largely unchanged, leading to the following conclusion:

$$C_{den}^{1} \approx C_{den}^{2} = 2 \bullet e^{-\lambda \bullet \frac{D_{\max}}{2}} = 1 \tag{4}$$

where $D_{\max}$ represents the distance beyond which the interaction between the two ships becomes insignificant.

For ships that are 50 m or longer, Rule 22 of the COLREGs specifies that the masthead light must be visible from a minimum distance of 6 nautical miles. Consequently, the distance $D_{\max}$ is generally assumed to be 6 nm in this research. Therefore, it can be calculated that λ = 0.231.

3.2.2. Ship Approaching Factor

When analyzing the approach trends of a pair of ships, both their positional proximity and the rate of change in that proximity are taken into account. To represent the positional proximity between ships, elliptical distance is utilized. The Ed_{ij} between ship i and ship j can be expressed as:

$$Ed_{ij} = \sqrt{\frac{(x_i - x_j)^2}{a_i^2} + \frac{(y_i - y_j)^2}{b_i^2}} \tag{5}$$

In this context, a_i and b_i denote the major and minor semi-axes of the elliptical ship domain, respectively. This paper employs the Fujii ship domain model, a well-established framework that has been extensively validated since its inception. Within the Fujii ship domain model, the ship's domain is represented as an ellipse, making it ideal for measuring the elliptical distance between ships and calculating their approach factor. Here, a represents the major semi-axis of ship i's domain, while b signifies the minor semi-axis. Given that inland waterways are typically narrow, a_i is set to $2L$ and b_i is set to $0.8L$, where L is the length of the ship [42]. The coordinates of the ship are denoted as (x, y). When the condition $Ed_{ij} < 1$ is met, one ship j's domain is encroached upon by ship i.

The rate of change in the positional proximity indicates how quickly two ships are closing the distance between them, which can be expressed as:

$$k_{ij}(t) = \frac{Ed_{ij}(t) - Ed_{ij}(t-1)}{Ed_{ij}(t-1)} \tag{6}$$

where k_{ij} represents the change rate of positional proximity between the pair of ships. If $k_{ij} < 1$, the ships are approaching each other. If $k_{ij} > 1$, the two ships are moving apart, with their relative distance continuously increasing. If k_{ij} equals 1, it indicates that both ships are sailing in parallel at the same speed.

Then, the approach factor between ship i and ship j can be formulated as:

$$C_{ap}^{ij} = \begin{cases} \left(\frac{1}{Ed_{ij}}\right)^{1+k_{ij}}, \ E_{ij} \geq 1 \\ \left(\frac{1}{Ed_{ij}}\right)^{1-k_{ij}}, \ E_{ij} < 1 \end{cases} \tag{7}$$

where C_{ap}^{ij} represents the ship approaching factor between ship i and ship j. As Ed_{ij} decreases, C_{ap}^{ij} increases, reaching a value of one or more when the ships are in conflict. A positive C_{ap}^{ij} indicates that the ships are moving apart, resulting in lower complexity. Conversely, a negative C_{ap}^{ij} signifies that the ships are closing in on each other, leading to higher complexity. In conclusion, this equation effectively models the complexity of the interaction between ships.

3.3. Complexity Measurement for Ship–OWF Relationship

After the construction of the OWF is completed, the existing maritime traffic flow will be significantly impacted. The navigation patterns of ships in the OWF area will be changed, and adjustments to their routes may be required to avoid the wind turbines, thereby increasing the complexity of navigation. To address this, a measurement was developed to describe the complexity relationship between ships and the OWF area.

The complexity relationship between ships and the OWF area takes into account the dynamic behavior of ships as they approach the boundaries of the OWF area, with the complexity of navigation being increased as the ships move closer to the boundary. This is because, near the OWF, navigation guidelines must be followed by the ship, and collisions with other ships and interference with the wind turbines must be avoided. As the distance between the ship and the OWF boundary decreases, the potential navigation risks and constraints are increased, leading to a rise in the overall navigational complexity.

The space proximity between ship i and the OWF o's boundary, denoted as D_{io}, is calculated as follows:

$$D_{io} = \begin{cases} \alpha e^{-|d_{io}-D_s|/D_s} & d_{io} > D_s \\ 1 & d_{io} \le D_s \end{cases} \tag{8}$$

where d_{io} is defined as the distance between ship i and the OWF o's boundary, and D_s is the safety distance from the OWF o's boundary. According to current regulations in China, the safety distance for OWF areas is set at 2 nautical miles.

α is an adjustment parameter representing the relative motion between the ship and the OWF area. If the ship is approaching the OWF area, the complexity between them is considered; otherwise, it is not. As shown in Figure 2, the area with the red-bordered box is the area generating complexity with ship i, while the area with the black dashed border can be disregarded. The calculation method for α is as follows:

$$\alpha = \begin{cases} 0, & \frac{\vec{v}\cdot\vec{b}}{|\vec{v}|\cdot|\vec{b}|} \le 0 \\ 1, & \frac{\vec{v}\cdot\vec{b}}{|\vec{v}|\cdot|\vec{b}|} > 0 \end{cases} \tag{9}$$

where $\vec{v}$ is the motion direction vector of the ship. $\vec{b}$ is the direction vector from the ship to the OWF o's boundary (the normal vector of the nearest boundary). When $\frac{\vec{v}\cdot\vec{b}}{|\vec{v}|\cdot|\vec{b}|} > 0$, it indicates that the ship is moving toward the boundary (approaching the OWF). When $\frac{\vec{v}\cdot\vec{b}}{|\vec{v}|\cdot|\vec{b}|} < 0$, it indicates that the point is moving away from the boundary (leaving the OWF). When $\frac{\vec{v}\cdot\vec{b}}{|\vec{v}|\cdot|\vec{b}|} = 0$, it indicates that the point is moving parallel to the boundary.

The changing rate as the ship approaches the OWF o's boundary is then calculated as follows:

$$V_{io}(t) = \frac{d_{io}(t) - d_{io}(t-1)}{d_{io}(t-1)} \tag{10}$$

Based on the spatial proximity and the approaching rate between ship i and OWF o's boundary, the complexity between them is calculated as follows:

$$C_{owf}^{io} = {D_{io}}^{1-V_{io}} \tag{11}$$

It can be seen that the range of C_{owf}^{io} is from 0 to 1. As the distance between ship i and OWF o's boundary decreases, the corresponding complexity gradually increases.

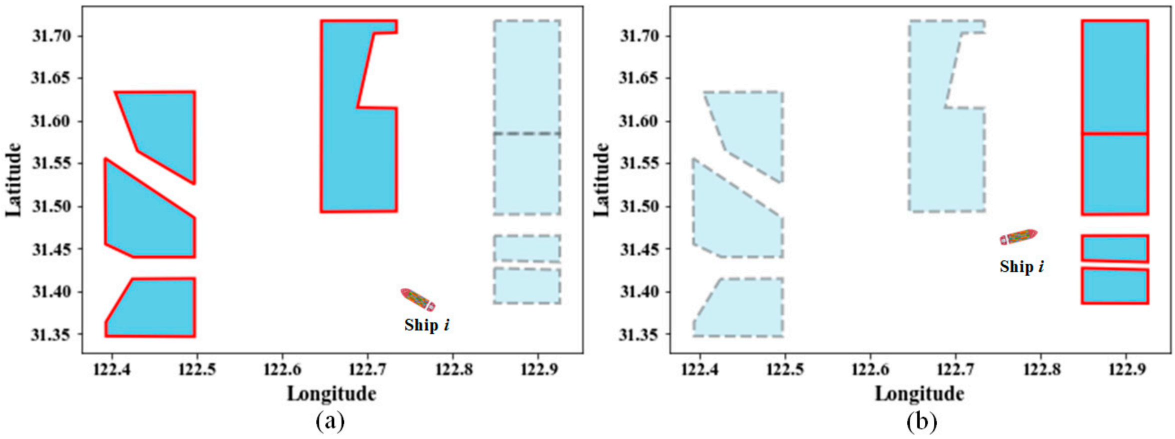

Figure 2. The relationship between ship and OWF area. (**a**) The relationship between ship *i* and A1–A4. (**b**) The relationship between ship *i* and A5–A6.

3.4. Global Complexity Evaluation

Due to the high traffic density, multi-ship encounters have become common in OWF areas. The complexity of these multi-ship encounters is greater and more serious than that of single ship-pair encounters, making it necessary to assess the overall complexity [43,44]. Given that there are n ships in the OWF area, the dynamic traffic density C_{den} for the n ships is calculated as:

$$C_{den} = \sum_{i=1}^{n} C_{den}^{i} = \sum_{i=1}^{n} e^{-0.231 s_i} \tag{12}$$

The ship approaching factor C_{ap} for the n ships is calculated as:

$$C_{ap} = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j \neq i}}^{n} C_{ap}^{ij} \tag{13}$$

The total amount of complexity between n ships and m OWF areas is calculated as:

$$C_{owf} = \sum_{i=1}^{n} \sum_{o=1}^{m} C_{owf}^{io} \tag{14}$$

The Min–Max standardization method is applied to normalize each indicator's value, allowing for a comprehensive consideration of the three factors. If a factor's value is represented as x, the standardized value x' is given by:

$$x' = \frac{x - x_{\min}}{x_{\max} - x_{\min}} \tag{15}$$

The maximum and minimum values of the factors are determined through the analysis of extensive historical data. Once the three factors have been standardized, the overall complexity is calculated as follows:

$$|C| = w_1 C'_{den} + w_2 C'_{ap} + w_3 C'_{owf} \tag{16}$$

where C'_{den}, C'_{ap}, and C'_{owf} are the standardized values of the three factors, and their corresponding weights are also represented as w_1, w_2, and w_3, respectively.

4. Results and Analysis

4.1. Comparative Analysis Before and After OWF Construction

AIS data from 31 July 2023, between 00:00 and 24:00, were selected for model validation. The three factors were assigned the same weight, each being 1/3. As shown in Figure 3, the red line reflects the trafneededfic complexity in the proposed OWF area, and the blue line reflects the traffic complexity without the OWF area. The change in the number of ships is shown in Figure 4.

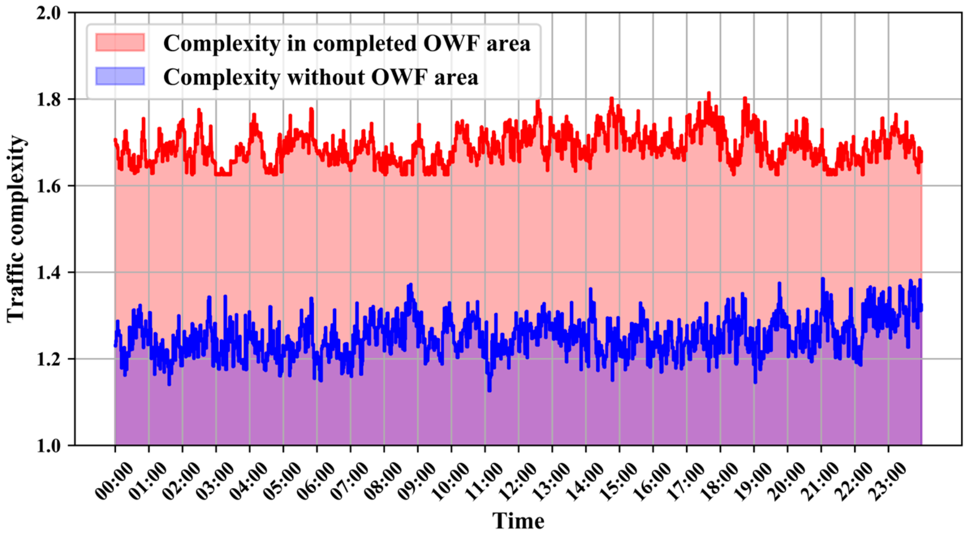

Figure 3. Comparison of traffic complexity before and after OWF construction.

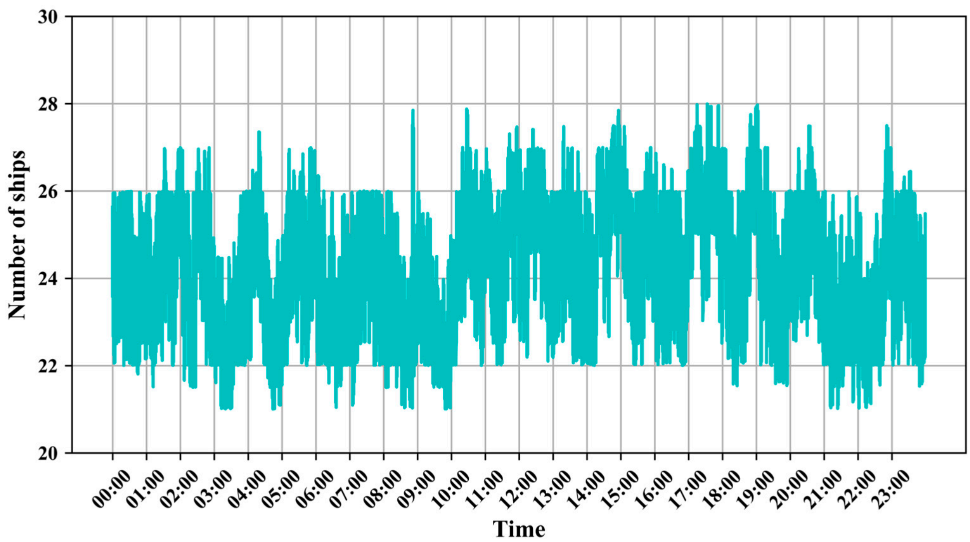

Figure 4. The change in the number of ships.

In the absence of the OWF's construction, the complexity of maritime traffic in this area is primarily influenced by density and proximity factors. Specifically, the density factor reflects the distribution of ships within the area and the overall traffic volume—the higher the ship density, the more complex the navigation environment. The proximity factor, on the other hand, indicates the distance and relative closeness between ships—the closer the ships are to each other, the higher the potential collision risk and, consequently, the complexity. In this context, traffic complexity is mainly driven by route congestion and ships' evasive maneuvers in high-density waters.

Overall, the navigational complexity shows a gradual upward trend, suggesting that over time, the relative movements of ships in the monitored area have become more complex, possibly due to an increase in the number of ships or dynamic changes in their movements. Frequent peaks and troughs in the graph reflect sudden changes in ship movements. This may relate to instantaneous traffic congestion, ships approaching or departing from the OWF area, or maneuvers such as turning, slowing down, or accelerating. For instance, when the relative distance between ships decreases, their speed changes dramatically, or their direction shifts, navigational complexity may spike, creating peaks. At certain points, complexity values sharply rise and quickly drop; this "spike" may result from a sudden decrease in ship distance or a group of ships approaching a specific area. These abrupt changes typically reflect high-density clustering or rapid turning of ships, causing a significant increase in navigational complexity over a short period. Although navigational complexity fluctuates, there is a slow upward trend, suggesting that ship activities in the area are becoming more frequent.

The changes in complexity after the completion of the OWF construction are illustrated by the red line in Figure 3. Overall, the red line is significantly higher than the blue line, clearly indicating that the presence of the OWF area indeed increases the complexity of navigation. The shaded area between the red and blue lines represents the additional complexity induced by the construction of the OWF. This phenomenon is not only visually represented in the graph but also reflects the navigation challenges faced by ships under different circumstances. As can be seen from Figure 3, the impact of the OWF on navigation is not static; rather, it fluctuates over time and with varying traffic levels. This variability may be closely related to factors such as navigation conditions, weather conditions, ship traffic, and the operational status of the OWF. The size of the shaded area not only reflects the degree of complexity increase but also poses new demands for navigation management. For instance, during periods of heightened complexity, there may be a need for additional monitoring or guiding measures in the shipping lanes to reduce the risk of ship collisions. This means that during high-complexity periods, relevant management departments should consider increasing maritime patrols, enhancing AIS monitoring, and other measures to ensure navigational safety.

After the construction of the OWF, ships will frequently need to adjust their courses to avoid the OWF area, especially when the farm occupies traditional shipping routes. This not only results in changes to navigation routes but may also increase the travel time and fuel consumption of ships. Additionally, due to changes in ship speeds and narrower navigation channels, the safe distances between ships are reduced, further complicating operations and increasing the complexity of travel paths. This complexity not only poses challenges for crew decision-making but may also lead to decreased navigation efficiency. Therefore, these dynamic changes require shipping companies and relevant management agencies to adopt more comprehensive traffic management strategies to ensure the safety and efficiency of maritime operations. Navigational management systems need to continuously adapt to these changes in complexity, adjusting navigation planning and management measures in a timely manner. At the same time, ship operators should enhance their understanding of OWF areas and improve their ability to respond to complex navigational environments, ensuring that they can safely and efficiently complete their navigation tasks even after the construction of the OWF.

4.2. Traffic Complexity Analysis in Different OWF Areas

This study focuses on the impact of OWF construction on ship navigation. Therefore, this section provides a detailed analysis of traffic complexity within each proposed OWF area, based on the complexity assessment method outlined in Section 3.3. It is important to note that the complexity between ships and the OWF is not normalized in this section. The aim is to quantify and compare the navigation complexity characteristics of different OWF areas, revealing the potential impact of OWF construction on traffic safety in surrounding waters. Through such complexity analysis, not only can a scientific basis for OWF site selection be provided, but it can also inform the development of relevant navigation safety management measures. Figure 5 shows the changes in traffic complexity across different OWF areas from 00:00 to 24:00 on 31 July 2023.

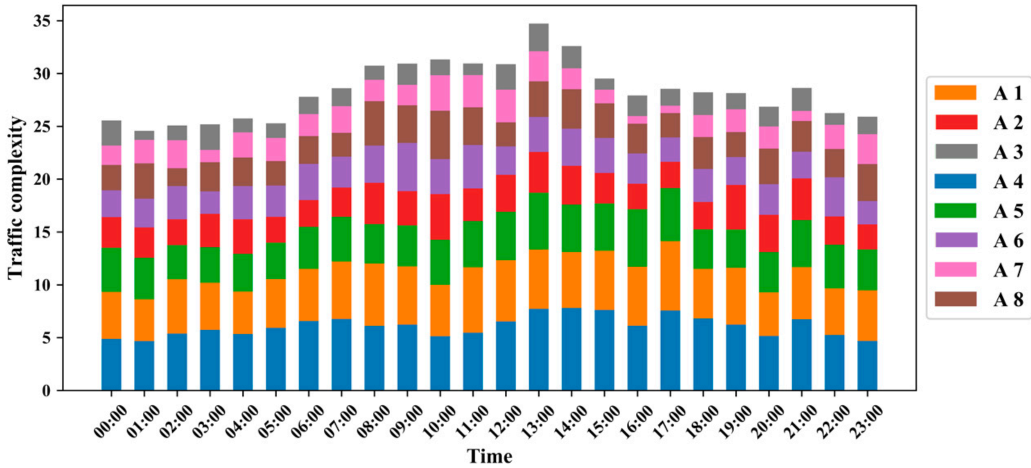

Figure 5. Complexity between different OWF areas and ships.

Further, data from July 2023 were selected to analyze the complexity between ships and the proposed OWF areas. The contribution of each proposed OWF area to the complexity of the research area is shown in Figure 6.

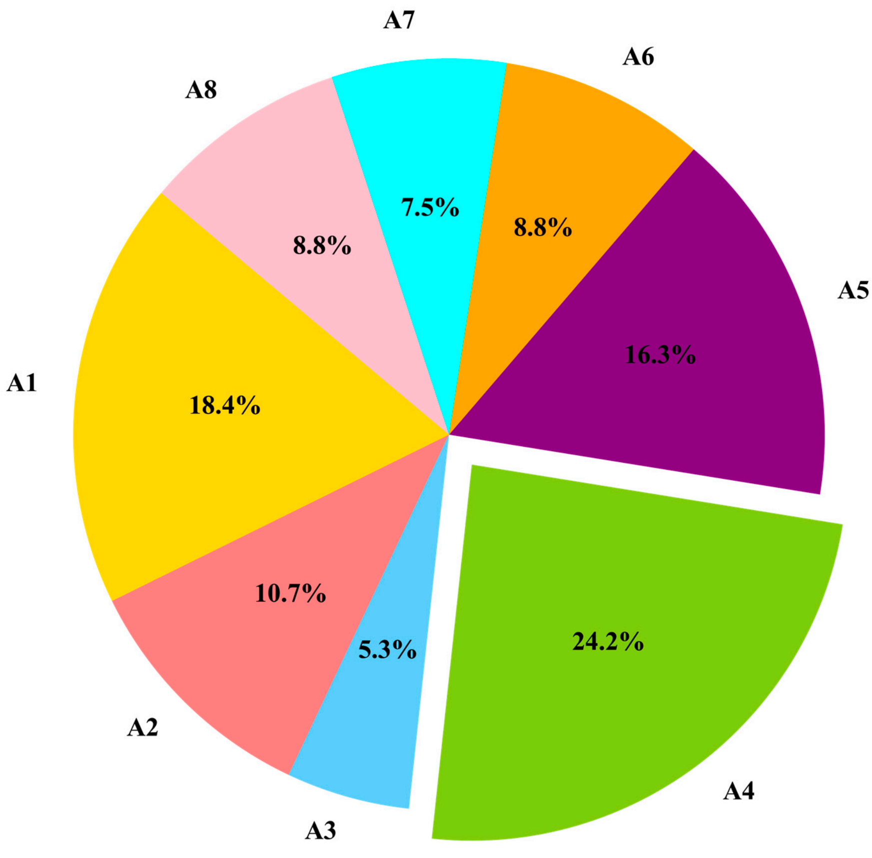

Figure 6. Contribution of different OWF areas to traffic complexity.

Based on the above analysis, it is evident that A4 contributes the most to the complexity of the research area. Since the proposed A4 occupies the habitual shipping routes, ships must adjust their courses, which may lead to an increase in crossing points and, consequently, a higher likelihood of collisions. This risk is particularly significant in low-visibility or adverse weather conditions, where ships have less reaction time, increasing safety risks. Once the OWF is completed, ships will need to navigate around the OWF area, potentially causing delays in travel time and increasing the risk of crew fatigue, especially in emergencies. In unexpected situations (such as mechanical failures or changes in weather), ships may struggle to find safe routes for evasion, raising the probability of accidents.

Adjustments in shipping routes may lead to a significant increase in traffic flow on certain pathways. For example, ships may opt for longer or busier routes, thereby affecting the overall traffic pattern. If multiple ships choose to detour via the same alternative route, it may result in congestion on that route, increasing the chances of delays and accidents. This situation can become more complex during peak times, where the concentration of ships may exacerbate the issue. The traffic load on alternative routes may exceed their designed capacity, leading to reduced navigation efficiency and potential safety hazards. Monitoring and managing these routes are essential to ensure smooth traffic flow. Over time, changes in ship traffic flow can impact the environment, economy, and regional development. Therefore, ongoing monitoring and assessment of traffic flow changes are crucial for formulating long-term management policies.

4.3. Contribution of Ship Types to Complexity Between Ship and Proposed OWF Area

The Yangtze River Estuary is an important shipping channel with very heavy traffic. It is not only a major domestic cargo transportation hub but also a key node in international shipping. The area hosts a diverse range of ship types, including cargo ships, tankers, container ships, and bulk carriers. Ships of different types and sizes exhibit significant variations in navigation behavior. For example, container ships typically sail at higher speeds and are suited for long-distance transport, while tankers require more safety distance to prevent accidents. Furthermore, due to the high concentration of industries near the Yangtze River Estuary, frequent ship traffic creates a complex traffic environment in the waters. This diversity of ship movements not only increases the complexity of navigation but also heightens the risk of collisions. In adverse weather conditions or low-visibility conditions, the responsiveness of various ships is limited, potentially leading to safety hazards. Therefore, understanding the complexity between different types of ships and proposed OWF areas is crucial for improving navigation safety and developing appropriate traffic management measures.

Figure 7 illustrates the distribution of ship types within the research area. Dry cargo ships are the most common type, making up 51.1% of the total traffic in the area, indicating a high volume of dry cargo transportation. Bulk carriers and multipurpose ships each account for over 12%, specifically 12.5% and 12.3%, respectively. This suggests a significant presence of ships capable of carrying various cargo types. Container ships and tankers represent 9.2% and 8.5% of the total, respectively, reflecting the area's importance for both containerized and liquid bulk cargo. A small proportion of ships, such as bulk cement carriers (1.2%) and salvage ships (0.9%), show the specialized nature of some traffic within the region. The remaining ship types each constitute less than 1% of the total, including liquefied gas carriers (0.6%), ro-ro ships (0.5%), and government and service ships (each below 0.5%). Other types, such as chemical tankers, workboats, dredgers, and tugboats, each account for a minor portion. The diverse range of ship types suggests a complex maritime environment, likely contributing to traffic complexity and navigation challenges, especially in areas where routes overlap. Specialized ships (such as chemical tankers and ro-ro ships) add unique risks and requirements for navigation, which could impact traffic safety and efficiency.

The complexity generated by the top-five-ranked ship types in the proposed OWF area was analyzed, as shown in Figure 8. When analyzing the traffic complexity between different types of ships and proposed OWF areas, the ships' navigation characteristics, sailing speed, and their interaction with the proposed OWF area need to be considered. The impact of different ship types on traffic complexity can vary significantly. In analyzing the traffic complexity between these ship types and the proposed OWF area, the navigational behavior and potential impact of each ship type on the proposed OWF area should be taken into account.

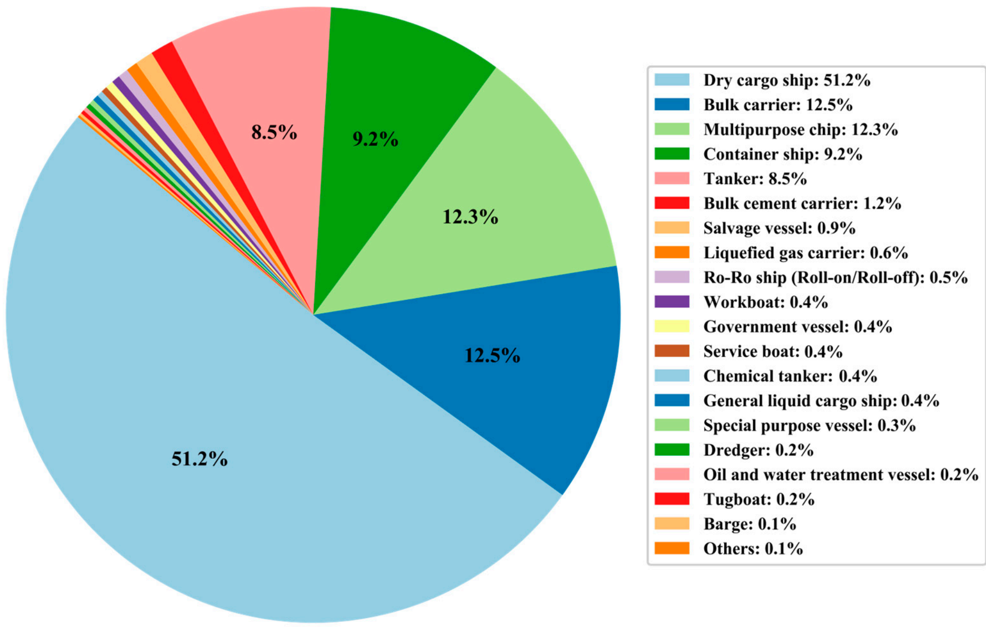

Figure 7. Distribution of ship types in the research area.

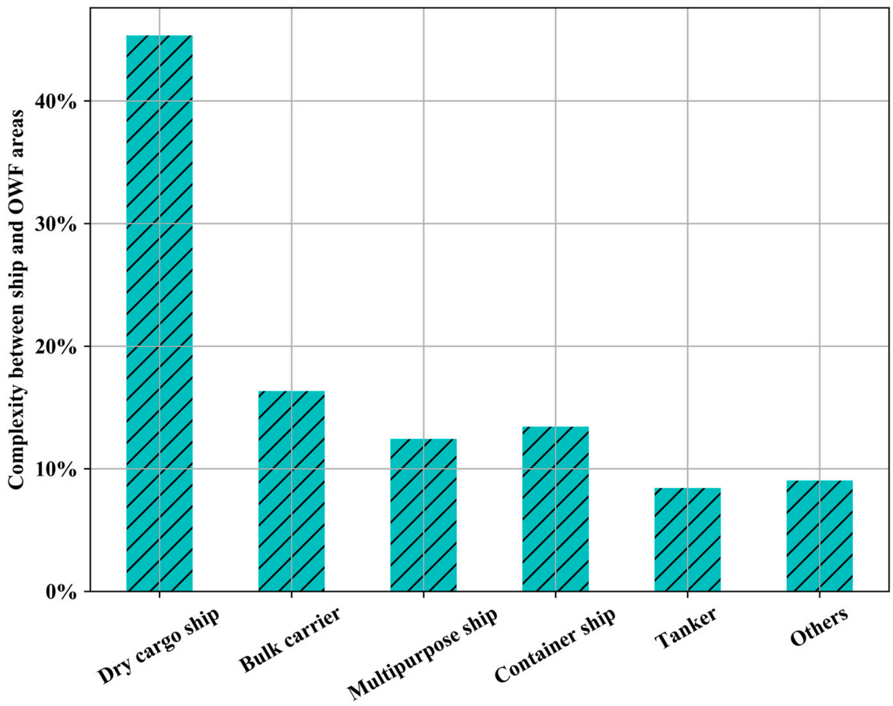

Figure 8. Complexity generated by the top-five-ranked ship types.

Dry cargo ships are the primary ship type in this region and have the greatest impact on the traffic complexity around the proposed OWF. This type of ship usually carries a large amount of cargo and has poor maneuverability, especially in narrow waters or areas that require frequent turns. When navigating near the OWF, if dry cargo ships need to adjust their course to avoid the proposed OWF, complexity may increase, particularly in areas with a high traffic density or intersecting routes. Due to their high inertia, dry cargo ships are slow to react in sudden situations, raising the likelihood of accidents near the proposed OWF. Bulk carriers, which account for a significant proportion of ships in the research area (approximately 12.5%), typically transport large volumes of bulk cargo and have limited maneuverability due to their heavy loads. When the proposed OWF blocks their usual route, bulk carriers need to take detours, which can increase traffic pressure in overlapping routes and thus raise navigational complexity. Multipurpose ships, which have flexible cargo capabilities and often carry diverse cargo types, have a maneuverability between that of bulk carriers and container ships. Given their relatively high navigational flexibility, multipurpose ships have a lower impact on the proposed OWF area, although route adjustments may still be necessary during periods of high traffic, contributing to an increase in complexity. Container ships generally travel at high speeds and have stringent requirements for navigational conditions, needing to pass through with minimal safe distance. The construction of the OWF may force container ships to adjust their routes or even slow down to detour, potentially causing route-crossing risks and, particularly during peak times, traffic bottlenecks. Tankers usually transport flammable, explosive liquid cargo, which demands high safety standards. They have limited maneuverability and travel at slower speeds, necessitating a larger safety buffer when near the OWF, which may increase navigational complexity for other ships. Other smaller specialized ships (such as LPG carriers, chemical carriers, barges, etc.) make up a smaller percentage of the traffic but require high safety standards, especially chemical and LPG carriers, which need stringent risk controls. When these ships adjust their routes due to OWF obstructions, they may contribute to traffic congestion, particularly in high-traffic areas, and their hazardous cargo introduces additional risk factors.

5. Discussion

With the construction of OWFs occupying parts of existing routes, ships need to adjust their courses to avoid the OWFs, significantly impacting the traditional route layout. These adjustments may result in longer travel paths, increased travel times, and higher fuel consumption. This is especially problematic in high-density-traffic areas, where such changes exacerbate congestion and elevate collision risks. The complexities brought about by route reconfiguration particularly affect large, low-maneuverability ships such as tankers and cargo ships, whereas smaller and more agile vessels are comparatively less impacted. This finding highlights that different ship types experience varying levels of complexity within OWF areas, with larger ships often requiring greater safety distances and navigation space, which, in turn, increases navigational complexity. Additionally, OWF construction introduces certain interferences with the navigation equipment of surrounding vessels. OWF structures can create obstacles on radar, potentially compromising the accurate detection of surrounding ships' positions and distances and thereby reducing situational awareness. This interference becomes more pronounced in low-visibility or adverse weather conditions, where ships approaching OWF areas may encounter navigation errors, heightening collision risks. Thus, more effective navigational assistance systems are required to address the limitations of traditional equipment within OWF areas.

In response to these challenges, several optimization recommendations are proposed. First, layered route planning specifically for OWF areas should be implemented to alleviate congestion resulting from route adjustments, particularly by providing more suitable navigable paths for large, low-maneuverability vessels. Second, it is recommended that OWF managers and maritime authorities collaboratively promote route optimization efforts, integrating real-time AIS data and big data analysis techniques to dynamically adjust for ship types and traffic flow. Early warnings for high-complexity periods can facilitate timely adjustments to travel routes or speeds, mitigating risks during peak traffic. Future OWF planning should avoid major shipping lanes or high-density traffic areas whenever possible and fully consider the navigational needs of different ship types to minimize the impact on existing route systems. Finally, relevant management authorities should continuously monitor and assess navigational risks in OWF areas, increasing surveillance and support measures during high-complexity and high-risk periods to ensure vessel safety.

6. Conclusions

This study developed a novel maritime traffic complexity model specifically for OWF areas, addressing a critical gap in current maritime safety research. The findings show that the proposed OWF significantly increases navigational complexity in high-density traffic areas, as evidenced by increased route congestion, changes in navigation patterns, and higher encounter rates among ships. The Yangtze River Estuary, a region characterized by dense and diverse traffic, provided an ideal environment for evaluating these dynamics. By comparing traffic complexity before and after the OWF's construction, this research offers strong empirical support for the anticipated navigational challenges in the proposed OWF areas.

This study not only provides a practical framework for assessing and managing maritime traffic complexity in the proposed OWF areas but also emphasizes the necessity of proactive policies and technological upgrades in these increasingly congested waters. However, the maritime traffic system is extremely complex, especially in OWF areas. Research on the complexity of maritime traffic in these areas is still in its early stages, and to accurately describe the traffic dynamics in OWF areas, a more comprehensive understanding of the composition and characteristics of the traffic system in these waters is needed. Future research could further enhance this model by incorporating real-time data and environmental variables to improve predictive accuracy. There are several issues with the proposed method that require further in-depth exploration and supplementation. AIS data were used in this study, but the potential incompleteness of the AIS data may still introduce some uncertainty. In future work, more reliable data sources will be incorporated, and data collection methods will be continuously improved to further enhance the accuracy and completeness of the data. Although a complexity model for maritime traffic in OWF areas was proposed in this research, human factors were not considered. Since most accidents are caused by human factors, future research could focus on obtaining real-time behavioral data related to the Officer on Watch (OOW) through relevant sensors, such as electroencephalogram (EEG) data and eye movement data, to study traffic situation complexity. While this study considered the relationship between ships and OWFs, it did not take into account the impact of ship type and maneuverability on complexity. In practical navigation, ship type is a very important factor. For example, oil tankers, LNG carriers, and passenger ships should receive more attention than other cargo ships when navigating in OWF areas. Therefore, future research should consider this factor. This study lays a solid foundation for developing more robust traffic management practices, ultimately supporting the safe and sustainable development of OWFs in critical maritime corridors.

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