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Applying the fuzzy distinction method to analyze the precautionary area of the wind farm along the western coast of Taiwan

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In recent years, Taiwan has undertaken significant efforts to establish and develop offshore wind farms (OWFs) in its western coastal region. Previous studies on precautionary area (PA) planning have predominantly focused on ship traffic density, while ignoring marine environment protection issues, revealing a gap in comprehensive analysis. Therefore, the study examines Taiwan's western offshore wind farm (OWF) area and develops a precautionary area (PA) planning model. The new PA concept considers not only navigational safety but also ecological sensitivity, as well as wind and hydrological factors. This approach aims to harmonize different marine activities, ensuring sustainable and efficient development of Taiwan's green energy sector. Firstly, this study collected ship navigation data from the automatic identification system (AIS). Secondly, the AIS data were processed and analyzed through a marine geographic information system (MGIS) for a detailed spatial analysis of the marine environment. Thirdly, fuzzy logic control (FLC) is used to manage marine data's inherent uncertainties and complexities, creating a more adaptable and nuanced model. By integrating AIS, MGIS, and FLC, the study develops an alternative PA planning model that enhances navigational and ecological safety while planning offshore wind farms. The alternative PA could facilitate the sustainable growth of Taiwan's green energy sector.

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Introduction

With the intensification of the atmospheric crisis and the impacts of the first oil crisis, countries worldwide have realized the importance of energy diversification and security. The drastic fluctuations in oil prices have not only affected the cost of living for the general public but have also had a profound impact on industrial production, transportation, and global supply chains, thus affecting the global economy (Alpanda and Peralta-Alva 2010). To address the energy crisis, countries worldwide have begun investing more in the development of renewable energy and nuclear energy to reduce their dependence on fossil fuels, which has also driven a transformation in energy policies and technological innovation. When fossil fuels and nuclear energy fail to provide sustainable and secure energy supplies, renewable energy has begun to gain more attention. Common types of renewable energy include solar energy, wind energy, hydroelectric energy, biomass energy, geothermal energy, and marine energy (Ang et al. 2022). Among these, wind power has gained support and investment from governments worldwide due to its enormous development potential. According to the statistical data from the Global Wind Energy Council (2024), as of 2023, the global offshore wind power capacity has reached 75.2 GW (Gigawatts), with 10.8 GW of new capacity added that year. Taiwan accounts for 6% of the total capacity.

Taiwan is an island nation surrounded by the sea and located in a subtropical monsoon region, offering stable and abundant wind resources. The weather conditions provide a unique advantage for the development of wind power. However, wind turbines are often considered undesirable facilities due to the limited land areas and proximity to densely populated areas. Building wind turbines offshore not only offers a larger area compared to land but also helps avoid issues like noise pollution that may affect nearby residents. Therefore, offshore wind power development has become a key focus of Taiwan's renewable energy strategy (Yue et al. 2019). Offshore wind power can provide clean, pollution-free electricity and reduce Taiwan's dependence on imported energy.

In recent years, Taiwan has actively developed offshore wind farms (OWFs) through various strategies and incentives, including attracting direct investment, announcing candidate sites for OWFs, and leading large-scale development. Currently, Taiwan has established several operative offshore wind farms (OWFs) around the western coast of Taiwan, including Formosa I, Formosa II, Taiwan Power Company Offshore Wind Farm Phase I, Changfang & Xidao, Greater Changhua I, and Greater Changhua II.

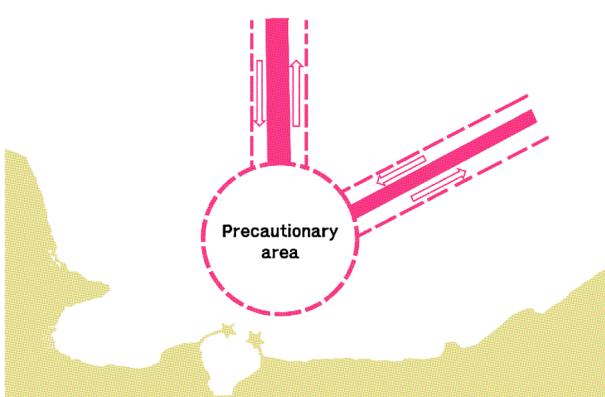


Fig. 1 PA diagram. The red areas represent fairways; the yellow areas represent shorelines.

Recently, navigation safety and navigation risk assessment in offshore wind farms have been critical and a hot issue. Therefore, Taiwan actively develops intelligent navigation safety plans for western Taiwan wind farms by utilizing marine GIS (MGIS). For navigation safety, the spatial supporting platform has been employed in the vessel traffic service (VTS) for the Taiwan channel monitoring mission by using MGIS. Additionally, Taiwan is actively developing a 4D smart port management system using the 4D metaverse technology.

However, the development of offshore wind farms (OWFs) inevitably faces resource competition and may encroach on the rights of other maritime users (Tsai et al. 2022), such as fishing boats and commercial vessels. In light of this, planning appropriate shipping channels and precautionary areas (PA) is critical.

The area within the proposed OWF sites in western Taiwan includes many fishing ports along the western coastline. The construction of OWFs will compress the fishing areas traditionally used by fishermen, potentially posing a risk of accidents to fishing vessels. Furthermore, when commercial vessels navigate near wind farms or enter planned shipping channels and PA, there is a potential risk of collisions that could damage the vessel's hull or wind turbine structures, leading to oil or chemical spills and causing environmental pollution, as well as the potential for casualties. Therefore, it is important to give significant attention to vessel collisions with wind turbines (Moulas et al. 2017).

Shipping channels and PA are crucial safety measures, particularly in areas with complex traffic flow and higher collision risks (Li et al. 2015). The authorities typically plan PAs in high-risk maritime areas, and vessels must wait outside the area for confirmation from relevant maritime authorities before entering. Additionally, vessels are required to exercise heightened caution while navigating within these areas (International Maritime Organization 1985). The function of a PA is similar to a traffic intersection on land, often located where multiple shipping channels or roads converge (Fig. 1). Traffic flow in these areas comes from various directions, making collisions or other safety incidents highly likely (Pietrzykowski and Magaj 2017). Strengthening the management and rational planning of PAs can effectively improve traffic safety levels and significantly reduce accident probabilities to ensure the safety of all vessels and related maritime facilities within the areas.

Yu et al. (2025) noted that identifying navigation risk in the waters of offshore wind farms (OWFs) using traditional probabilistic methods is challenging due to various impact factors and limited accident records.

Tsai et al. (2023) applied the fuzzy Delphi method to identify risk attributes and adopted a fuzzy decision-making trial and evaluation laboratory method to examine the interrelationships between attributes in the offshore wind farms.

Based on the limitations and uncertainties of the methodology, previous studies may result in an overestimation of navigation risks. Therefore, Rawson and Brito (2022) suggested that future studies focus on supporting decision-makers in spatial planning to mitigate the overestimation of navigation risks.

Previous studies have explored maritime-related issues using fuzzy methods (Kao et al. 2020; Liu et al. 2021; Fiskin 2023) and Multi-Criteria Decision Making (MCDM) (Silveira et al. 2021; Chou et al. 2022; Yu et al. 2022). Scholars have utilized AIS data to treat vessel draft, sea states, and vessel length as fuzzy linguistic variables, thereby developing the Jin-Xia channel model to analyze the navigability and safety of shipping channels (Su et al. 2019). While many studies have applied fuzzy theory and GIS for maritime safety analysis, research on PA planning remains limited. This study investigates the feasibility of the new PA planning method for maritime safety in Taiwan's OWF areas. It combines fuzzy theory

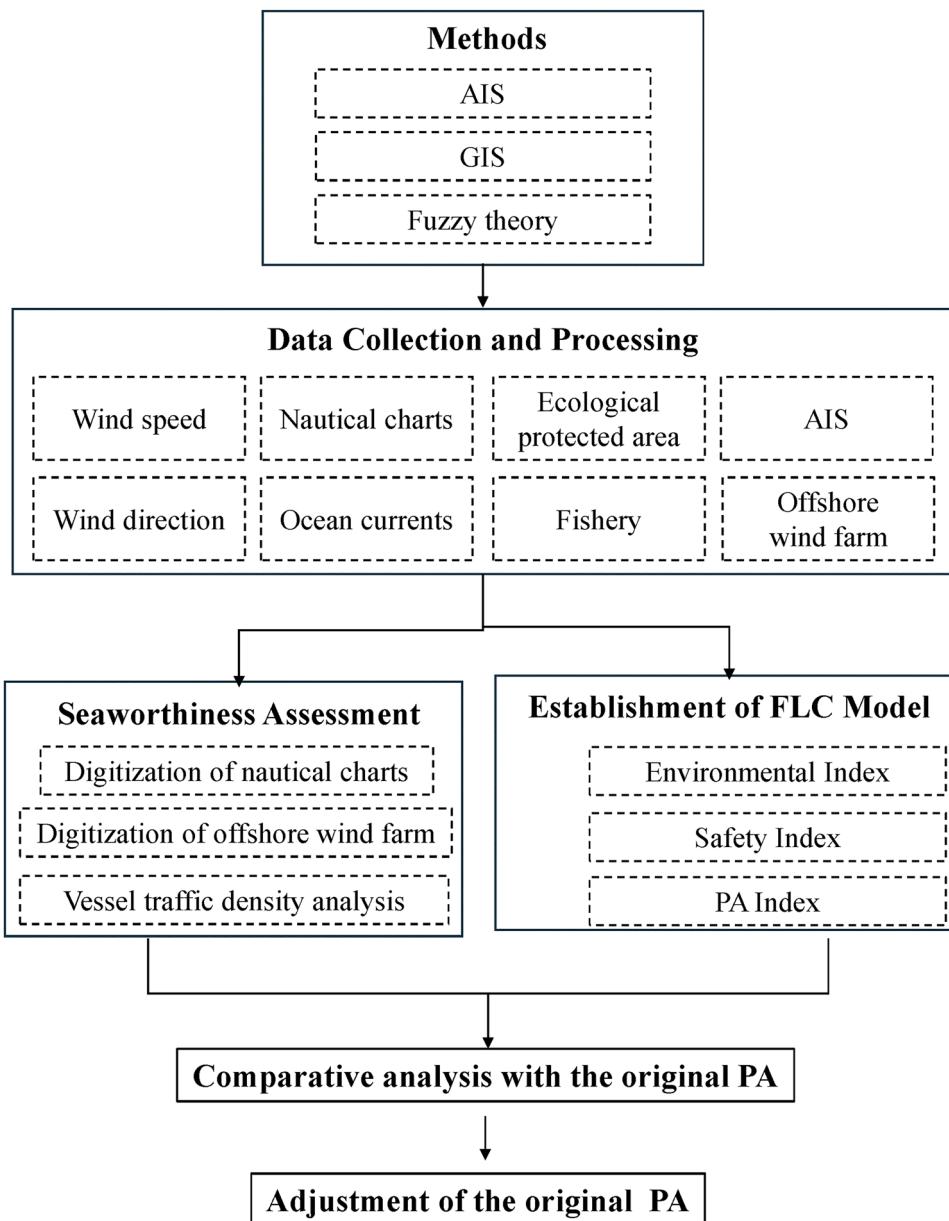


Fig. 2 The research framework. The boxes with solid lines represent research components. The boxes with dashed lines represent subcomponents.

with MGIS, integrates AIS data with sustainability criteria, and compares the output results with the initial PA recommendations proposed by the government to enhance Taiwan's future maritime safety and promote the green energy industry. Therefore, the objective of the paper is to create a data integration framework and to further serve as a policy analysis tool. Finally, this study identified the present PA area and proposed related policy recommendations by using the data integration framework of PA.

Methods

Figure 2 illustrates the overall study process. The research methodologies used in this study encompass the AIS, GIS, and fuzzy theory. In the first step, the study collected the necessary data, including wind speed, wind direction, nautical charts, ocean currents, ecological protected areas, fisheries, ship AIS data, and offshore wind farm data. And then deleted abnormal AIS data. The second step involves assessing seaworthiness and establishing the FLC model, respectively. To assess the seaworthiness of the channel, this study digitizes the nautical charts and the offshore

wind farms, and analyzes the traffic density of vessels on the channel. In addition, this study also establishes the environmental, safety, and PA indices to develop the FLC model. The third step is to compare the obtained PA with the original PA. It offers some policies and suggestions for adjusting the original PA.

This study utilized the fuzzy logic control (FLC), the marine GIS and the local AIS base stations to track marine traffic in Taiwan's near-shore waters. The local AIS base stations were installed by National Taiwan Ocean University, which provide internationally approved, validated, and categorized data in a formatted manner.

Automatic identification system. An automatic identification system (AIS) is a technology used for communication and positioning between vessels and between vessels and shore-based stations. It was initially designed to improve navigation safety and is now used for monitoring vessel traffic, managing harbor traffic flow, and executing maritime safety-related tasks. AIS operates in accordance with regulations established by organizations such as the International Maritime Organization and the International

Association of Marine Aids to Navigation and Lighthouse Authorities. In addition, the International Convention for the Safety of Life at Sea (SOLAS), which came into force in 2000, specifies in Chapter V, Regulation 19, that vessels with 300 gross tonnage or greater on international routes, vessels with 500 gross tonnage or greater on non-international routes, and all passenger vessels must be equipped AIS, which must remain operational at all times. This regulation mainly covers the following items (International Maritime Organization 2002):

- (1) Provide information: Vessel identity, type, position, speed, navigation status, and other safety-related information.
- (2) Automatically receive information from other vessels.
- (3) Monitor and track vessels.
- (4) Exchange data with shore-based stations.

Table 1 AIS data transmission rate of Class A devices.

Vessel's dynamic conditions	Nominal reporting interval
Vessel at anchor or moored and not moving faster than 3 knots	3 min
Vessel at anchor or moored and moving faster than 3 knots	10 s
Vessel 0–14 knots	10 s
Vessel 0–14 knots and changing course	3.33 s
Vessel 14–23 knots	6 s
Vessel 14–23 knots and changing course	2 s
Vessel >23 knots	2 s
Vessel >23 knots and changing course	2 s

AIS integrates technologies such as the Global Positioning System (GPS) and Very High Frequency (VHF) radio, using two channels in the VHF range—87B (161.975 MHz) and 88B (162.025 MHz)—for data transmission and reception. AIS shipborne equipment is classified into Class A and Class B. Vessels regulated by the SOLAS convention are required to be equipped with Class A devices. Table 1 shows the data transmission rate for these devices.

Marine geographic information system. A geographic information system (GIS) combines software, hardware, data, and analytical tools to allow users to visualize and understand various geographical phenomena and the spatial relationships of different types of spatial data. A basic GIS includes spatial data, attribute data, coordinate systems, and layers. Spatial data can be divided into two main types: vector data, which consists of points, lines, and polygons, and raster data, which consists of grids. These are overlaid in multiple layers for computational and analytical purposes. In recent years, scholars have applied GIS data, concepts, and tools in the marine field, resulting in the development of the marine geographic information system (MGIS).

This study used the Create Fishnet function in ArcGIS Pro to grid the offshore wind farm (OWF) area, with the grid range based on the proposed PA plan by the Taiwan Maritime and Port Bureau (MPB). The grid dimensions are set to 2 nautical miles, based on the safety distance between two encountering vessels (Hsu 2014), with 13 rows and 13 columns, totaling 169 grids (numbered from 0 to 168). The center point of each grid, referred to as the grid label, is set to ensure the precise calculation of the vector data. Furthermore, this study uses MGIS to map the

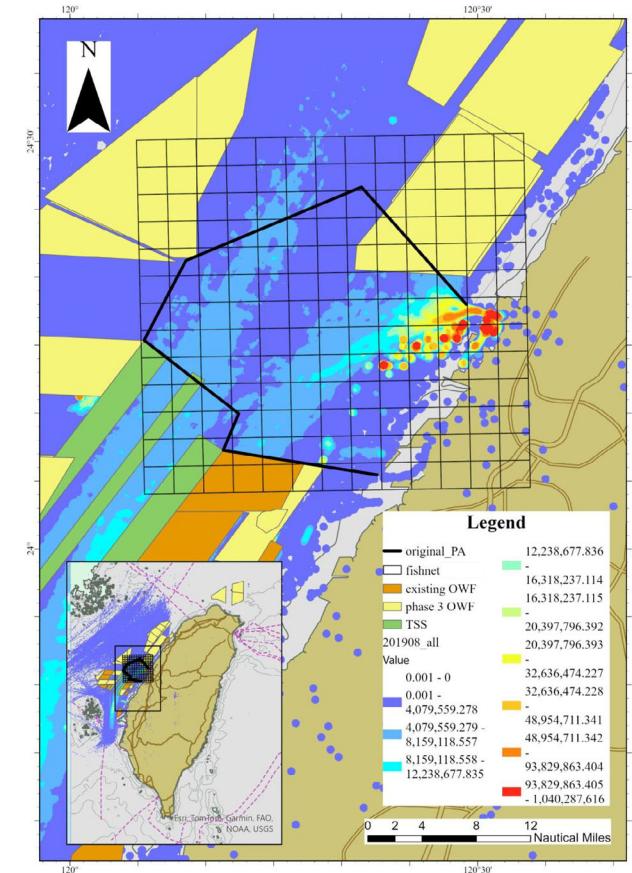
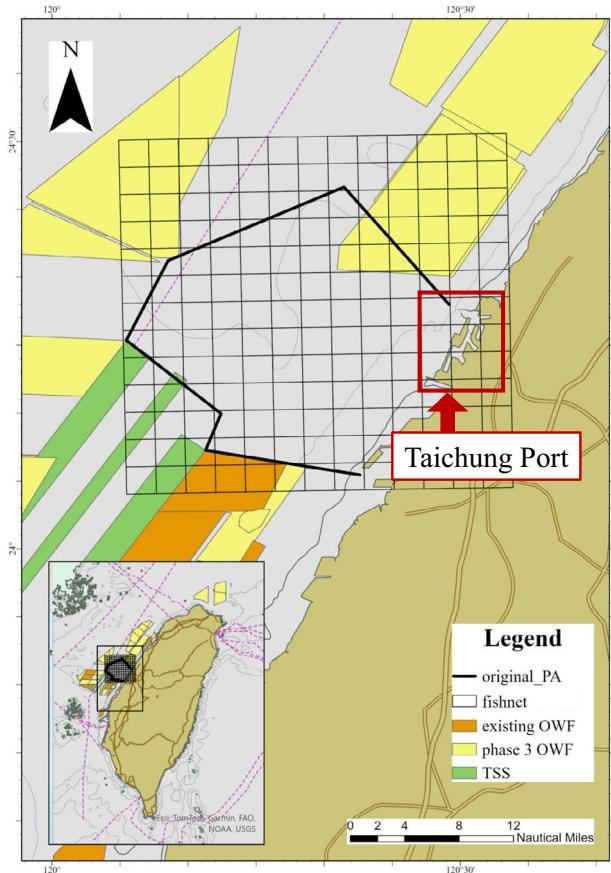


Fig. 3 Spatial data displayed in MGIS. The area with 13 rows and 13 columns, totaling 169 grids in the left figure, represents the wind farm. The various colors in the wind farm of the right figure represent the density of vessel traffic.

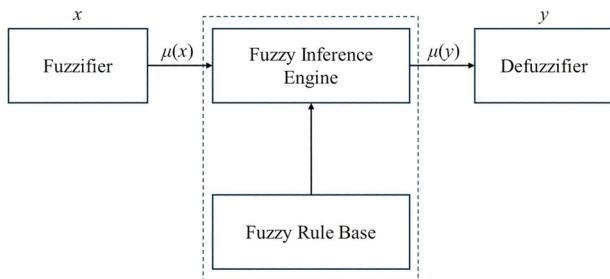


Fig. 4 FLC system structure. The boxes represent the components of the fuzzy logic control system.

polygon areas of the existing OWF areas, the third-phase planning areas, and the traffic separation scheme (TSS) channels off the coast of Changhua in western Taiwan, as shown in Fig. 3a. Vessel traffic density and fishery resource density are estimated using Kernel density estimation (KDE), where long-term vessel AIS data and fishery data were plotted as density flow layers, as shown in Fig. 3b.

Fuzzy theory. Zadeh (1965) proposed the original fuzzy theory. Its core concept is the fuzzy sets, which differs from traditional sets based on binary logic that only have two extreme values—“belong” or “do not belong”—without any gray areas. However, in reality, human thinking logic is not limited to just 0 or 1. For example, there is no specific boundary for the degree of temperature; using binary logic would not provide practical information. Fuzzy sets use membership functions to create a range between 0 and 1 and represent the degree to which a value belongs to the set with a membership degree. The closer the degree is to 1, the higher the membership degree. Fuzzy sets align more closely with human thinking patterns and natural language, offering greater flexibility in handling complex real-life problems. In recent years, the fuzzy theory has been applied to various fields, particularly in decision-making and renewable energy evaluation (Du et al. 2022; Hussain, Ullah, Senapati et al. 2024; Hussain, Yin, Ullah et al. 2024; Zeb et al. 2024).

Figure 4 shows the basic structure of fuzzy logic control (FLC), which includes fuzzifier, fuzzy rule base, fuzzy inference engine, and defuzzifier. First, the fuzzifier converts precise input data into fuzzy numbers, where membership functions are used to map the input data to fuzzy sets with fuzzy meanings. This study fuzzified the initial precise data to triangular fuzzy numbers. The fuzzy rule base is created using multiple fuzzy rules based on IF-THEN statements. The rules are generally formulated based on expert experience or historical data, and the membership degree of the input data is calculated to determine which rules are triggered. The fuzzy inference engine simulates human thinking and decision-making patterns, performing reasoning with the fuzzy rule base and computing the fuzzy output.

This study utilizes the Mamdani fuzzy inference engine to address the uncertainty and fuzziness in the system. Its advantage lies in the rules being intuitive and easy to understand, and it integrates expert knowledge to simulate complex decision-making processes by setting reasonable rules (Mamdani and Assilian 1975; Pujaru et al. 2024). Finally, the fuzzy output values are transformed into clear and actionable output values in defuzzification. The Center of Gravity method is the most commonly used defuzzification technique. The final output value is obtained by calculating the centroid of the output function. Its advantage is that it considers the overall distribution of the fuzzy set, making the output results smoother and more accurate compared to other

methods (Yadav 2021). Equation (1) is the formula for the center of gravity method.

$$y(x) = \frac{\sum_{i=1}^N y_i \mu(y_i)}{\sum_{i=1}^N \mu(y_i)} \quad (1)$$

One of the challenges in building a decision-making system is the need to consider a large number of input variables. As the number of input variables increases in a fuzzy system, the complexity of designing the rule base also rises. It not only increases the difficulty of system design but also amplifies the risk of subjective judgment, which may lead to biased decision outcomes. To overcome this challenge, this study adopts a multi-layer fuzzy design approach, dividing the fuzzy model into multiple sub-models of lower complexity. Each sub-model is a two-input and one-output structure. This architecture helps simplify the overall system design, effectively lower the computational load, and reduce the complexity of the rule base. By processing the input variables layer by layer, the system can more accurately capture the nonlinear relationship between the input variables, thereby improving the accuracy and stability of the decision-making system. Based on this approach, the outputs of the sub-models are progressively combined into the final stage model, ultimately producing a comprehensive decision result, which makes the overall fuzzy model more flexible and adaptable (Balmat et al. 2011).

Fuzzy logic control model for precautionary area

The fuzzy logic control (FLC) model in this study consists of three phases and seven fuzzy sub-models (Fig. 5). Each fuzzy sub-model has two inputs and one output, where the output values serve as inputs for the next stage, utilizing triangular fuzzy numbers for calculation. This model aims to analyze the factors affecting the precautionary area planning and then decide the optimal PA. The first phase comprises four sub-models (aspects): wind factors (wind speed and wind direction), hydrological factors (ocean depth and ocean currents), ecological sensitivity (protected areas and fisheries), and navigational safety (traffic density and distance to OWF). The second phase involves the environmental index (comprising wind factors and hydrological factors) and the safety index (encompassing ecological sensitivity and navigational safety). Finally, the third phase uses the environmental index and safety index as inputs, with the output being the PA indicator value.

To analyze traffic density, AIS data surrounding the western waters of Taiwan is collected to obtain the vessel's parameters and geographical locations. Fishery data are sourced from the Department of Environmental Biology and Fisheries Science at National Taiwan Ocean University, utilizing pole-and-line fishing data. This less destructive fishing method more effectively protects fishery resources and minimizes environmental impact. Other data on wind, hydrology, ecological protected areas, wind farms, and shipping channels are sourced from government official data (Taiwan Ocean State Information Platform 2024). Table 2 shows the input data for the first phase of the fuzzy model, while Table 3 presents the parameters for each sub-model in the fuzzifier.

Fuzzification. Sections “Winfd factors”, “Environmental index (EI) and safety index (SI)”, and “Precautionary area index (PA)” show the fuzzification processes in the first, second, and third phases of the fuzzy logic control model, respectively.

Wind factors (WF). In Table 2, the data used in the FLC model include wind speed, wind direction, ocean depth, ocean currents, protected area, fishery, traffic density, and distance to OWF. This

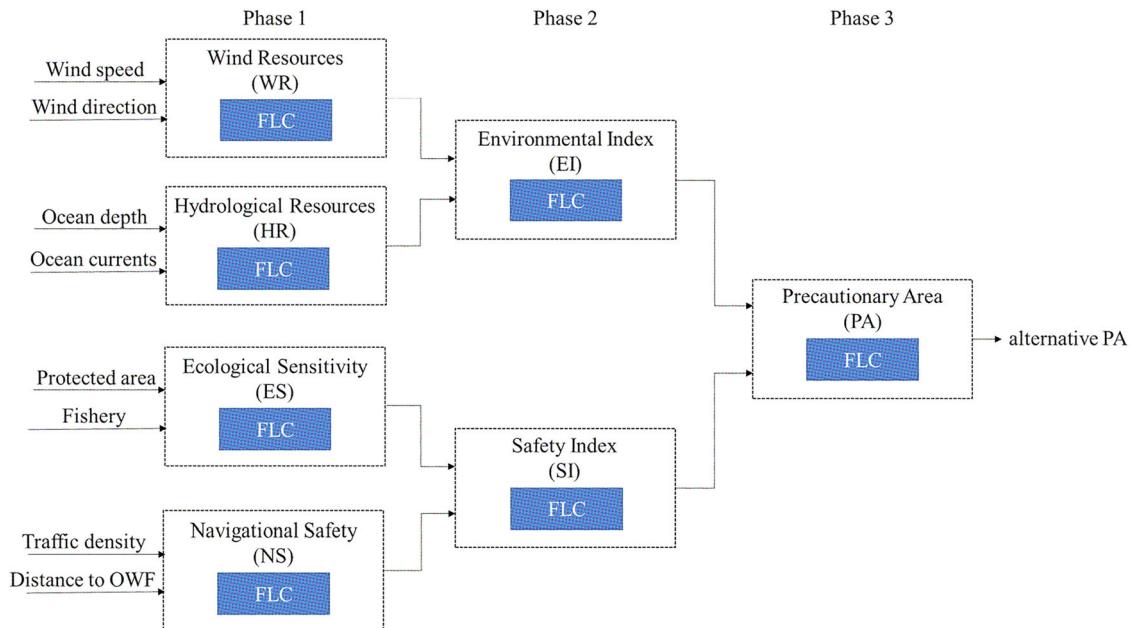


Fig. 5 Structure of FLC model for PA analysis. The boxes represent the indices of the fuzzy logic control system; the eight arrows on the left side represent eight variables.

Table 2 The input data for the first phase of the fuzzy model.

Parameters (Units)	Description	Values	Membership functions
Wind speed (m/s)	The min, average, and max wind speed.	2.62 5.75 6.85	Light Moderate Gale
Wind direction (degrees)	The min, average, and max wind direction (Based on the vessel's heading, the range extends from 0 to 90 degrees).	0 44.61 89.32	Small Medium Large
Ocean depth (meters)	The min, average, and max ocean depth.	2 42.11 63	Shallow Moderate Deep
Ocean currents (knots)	The min, average, and max ocean currents.	0.3 0.44 0.6	Light Moderate Fresh
Protected area (meters)	The min, average, and max distance to ecological protected area.	304.6 14924.2 41579.6	Close Moderate Far
Fishery (classes)	The min, average, and max fishery data (Use the KDE function in MGIS to classify the data).	1 3.79 23	Sparse Moderate Dense
Traffic density (classes)	The min, average, and max traffic density (Use the KDE function in MGIS to classify the data).	1 2.35 23	Sparse Moderate Dense
Distance to OWF (meters)	The min, average, and max distance to OWF.	47.7232 7675.17 23786.3	Close Moderate Far

section presents the fuzzification process of wind speed. The fuzzification processes of the other parameters are similar to that of wind speed. Thus, this section does not repeat the fuzzification processes for the other parameters, similar to the wind speed.

According to Table 2, the minimum, average, and maximum wind speeds are 2.62, 5.75, and 6.85 meters per second, respectively. Figure 6 presents the wind speed fuzzy set.

Table 3 The parameters for each sub-model in the fuzzifier.

Phase	FLC sub-model	Values	Membership functions
1	Wind factors (WF)	0 50 100	Bad Moderate Good
	Hydrological factors (HF)	0 50 100	Bad Moderate Good
	Ecological sensitivity (ES)	0 50 100	Bad Moderate Good
	Navigational safety (NS)	0 50 100	Bad Moderate Good
	Environmental index (EI)	0 50 100	Bad Moderate Good
	Safety index (SI)	0 50 100	Bad Moderate Good
	PA index	0 5 10	Bad Moderate Good

Equations (2) to (4) are the wind speed membership functions.

$$WS_{Light}(x) = \begin{cases} 1 & \text{for } x \leq 2.62 \\ \frac{5.75 - x}{3.13} & \text{for } 2.62 \leq x \leq 5.75 \end{cases} \quad (2)$$

$$WS_{Moderate}(x) = \begin{cases} \frac{x - 2.62}{3.13} & \text{for } 2.62 \leq x \leq 5.75 \\ \frac{6.85 - x}{1.1} & \text{for } 5.75 \leq x \leq 6.85 \end{cases} \quad (3)$$

$$WS_{Gale}(x) = \begin{cases} \frac{x - 5.75}{1.1} & \text{for } 5.75 \leq x \leq 6.85 \\ 1 & \text{for } 6.85 \leq x \end{cases} \quad (4)$$

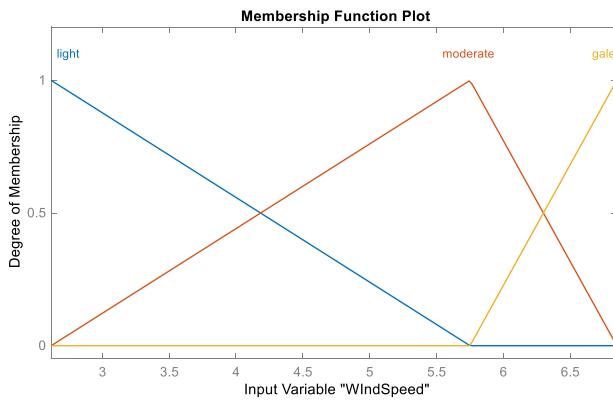


Fig. 6 Wind speed semantic fuzzy set. The lines represent the membership functions of fuzzy numbers.

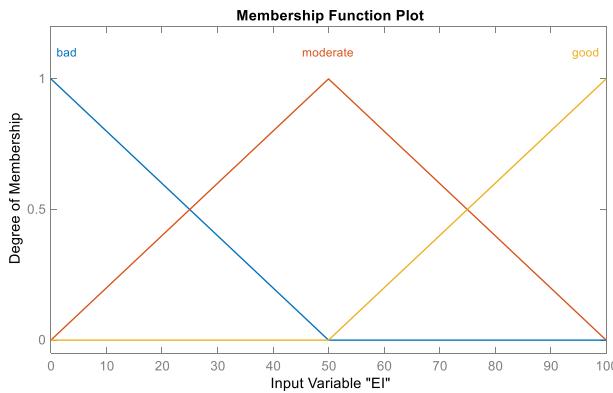


Fig. 7 EI semantic fuzzy set. The lines represent the membership functions of fuzzy numbers.

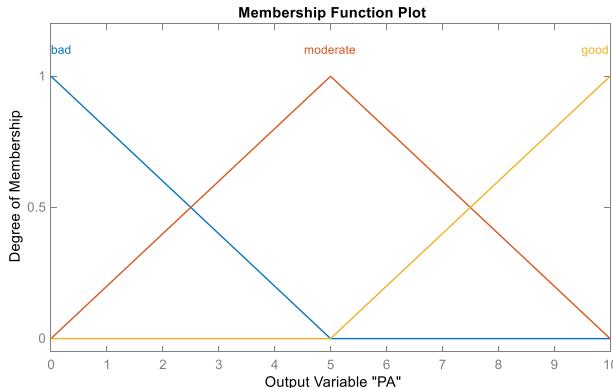


Fig. 8 PA semantic fuzzy set. The lines represent the membership functions of fuzzy numbers.

Environmental index (EI) and safety index (SI). When vessels navigate at sea, their track, stability, and speed are inevitably affected by various factors, such as sea states and environmental conditions. Strong winds and currents increase the torque exerted on the vessel, which can cause deviations from the planned route (Chen et al. 2015). The impact of water depth on vessel navigation is also significant. In deep waters, the distance between the vessel's hull and the seabed is greater, reducing the resistance encountered by the vessel. In shallow waters, however, the vessel's resistance increases substantially due to the shallow water effect, causing the vessel to pitch more severely and potentially leading to phenomena such as squatting, which could result in the vessel

sinking or the bow rising, thereby affecting navigation stability (Zhen et al. 2023). In this study, the EI variable is categorized into three levels: Bad, Moderate, and Good, defined as 0, 50, and 100, respectively, as shown in Fig. 7. When the EI value is close to 0, it affiliated with the EI_{Bad} function; when the EI value is close to 100, it affiliated with the EI_{Good} function, as shown in Eqs. (5) to (7).

$$EI_{Bad}(x) = \begin{cases} 1 & \text{for } x \leq 0 \\ \frac{50-x}{50} & \text{for } 0 \leq x \leq 50 \end{cases} \quad (5)$$

$$EI_{Moderate}(x) = \begin{cases} \frac{x}{50} & \text{for } 0 \leq x \leq 50 \\ \frac{100-x}{50} & \text{for } 50 \leq x \leq 100 \end{cases} \quad (6)$$

$$EI_{Good}(x) = \begin{cases} \frac{x-50}{50} & \text{for } 50 \leq x \leq 100 \\ 1 & \text{for } 100 \leq x \end{cases} \quad (7)$$

Regarding the safety index (SI), with the increasing restrictions of environmental regulations and heightened ecological protection awareness, the impact of vessel navigation on ecologically sensitive areas has gained more attention. Emissions of exhaust gases, oil pollution, and noise from vessels pose potential threats to marine ecosystems. Additionally, invasive species are more likely to be transported into local ecosystems via the vessel's hull or ballast water (Anil et al. 2002). Furthermore, when planning new shipping channels and PAs, consideration should be given to existing fishing areas to ensure that commercial shipping does not excessively disrupt fishing activities (Roberts et al. 2005). Additionally, the core objective of establishing PAs is to ensure the safety of vessel navigation. An ideal PA should be located at the intersection of multiple shipping channels in areas with higher traffic density. Vessels tend to choose routes with better navigation conditions, resulting in specific areas of the sea having higher traffic density (Wang 2019). OWF alters the wind and current environments in surrounding sea areas, which can affect the maneuverability of smaller or older vessels. When vessels approach OWF areas too closely, they may be forced to alter their predetermined routes, thereby increasing the risk of collision or grounding (Xie et al. 2019). In this study, the SI variable is categorized into three levels: Bad, Moderate, and Good, defined as 0, 50, and 100, respectively, similar to Fig. 7. When the SI value is close to 0, it is affiliated with the SI_{Bad} function; when the SI value is close to 100, it is affiliated with the SI_{Good} function, similar to Eqs. (5) to (7). Thus, this section does not repeat the figure and equations of the membership function for SI.

Precautionary area index (PA). The two inputs for the PA sub-model are EI and SI. When the EI score and the SI score are both high, it indicates that the conditions in the area are suitable for vessels to navigate. Conversely, when the EI score and SI score are both low, it suggests that the conditions in the area are not suitable for ships to navigate. In this study, the PA variable is divided into three levels: Bad, Moderate, and Good, defined as 0, 5, and 10, respectively. It enables the final output results to converge and be easily displayed, as shown in Fig. 8. When the PA value is close to 0, it is affiliated with the PA_{Bad} function; when it is close to 100, it is affiliated with the PA_{Good} function, as shown in Eqs. (8) to (10).

$$PA_{Bad}(x) = \begin{cases} 1 & \text{for } x \leq 0 \\ \frac{5-x}{5} & \text{for } 0 \leq x \leq 5 \end{cases} \quad (8)$$

$$PA_{Moderate}(x) = \begin{cases} \frac{x}{5} & \text{for } 0 \leq x \leq 5 \\ \frac{10-x}{5} & \text{for } 5 \leq x \leq 10 \end{cases} \quad (9)$$

$$PA_{Good}(x) = \begin{cases} \frac{x-5}{5} & \text{for } 5 \leq x \leq 10 \\ 1 & \text{for } 10 \leq x \end{cases} \quad (10)$$

Fuzzy rule base and fuzzy surface. The fuzzy inference engine primarily consists of IF-THEN statements that relate conditions and results. In the third phase of the fuzzy model in this paper, EI and SI are used as inputs to produce the PA indicator value. Among the 27 rules, 18 conflicting rules were removed, resulting in 9 remaining rules, as shown in Table 4. Figure 9 illustrates the fuzzy surface.

Table 4 Fuzzy rule base of PA sub-model.

Rules	EI	SI	PA
1	Bad	Bad	Bad
2	Bad	Moderate	Bad
3	Bad	Good	Moderate
4	Moderate	Bad	Bad
5	Moderate	Moderate	Moderate
6	Moderate	Good	Good
7	Good	Bad	Moderate
8	Good	Moderate	Good
9	Good	Good	Good

Defuzzification. This study uses the Center of Gravity method for defuzzification, obtaining a precise output value for the FLC model based on the convergence results. Figure 10 illustrates the defuzzification process. When both the EI and SI scores are 60, the PA output value is 5.11.

Research results

This study utilizes vessel traffic density data derived from AIS in western Taiwan to assess the feasibility of the PA in the offshore area of Taichung Harbor and the OWF waters. The PA index values output from the FLC model are compared and analyzed with the original PA in the OWF waters. Finally, the study gives relevant authorities and academic researchers conclusions and recommendations for reference.

Vessel traffic density analysis in the OWF area. This study collected AIS data and then created a traffic density map, which was then overlaid with the OWF, TSS areas, and nautical charts, as shown in Fig. 11. The blue-red color scale represented the vessel traffic density, with blue indicating areas of lower vessel traffic density and red indicating areas of higher vessel traffic density. From Fig. 11, we can observe that the vessel traffic density is higher near Taichung and Mailiao harbors. Additionally, vessels primarily concentrate in the northbound channel on the eastern side of the Changhua Offshore Wind Farm channel. However, since the Changhua Offshore Wind Farm channel

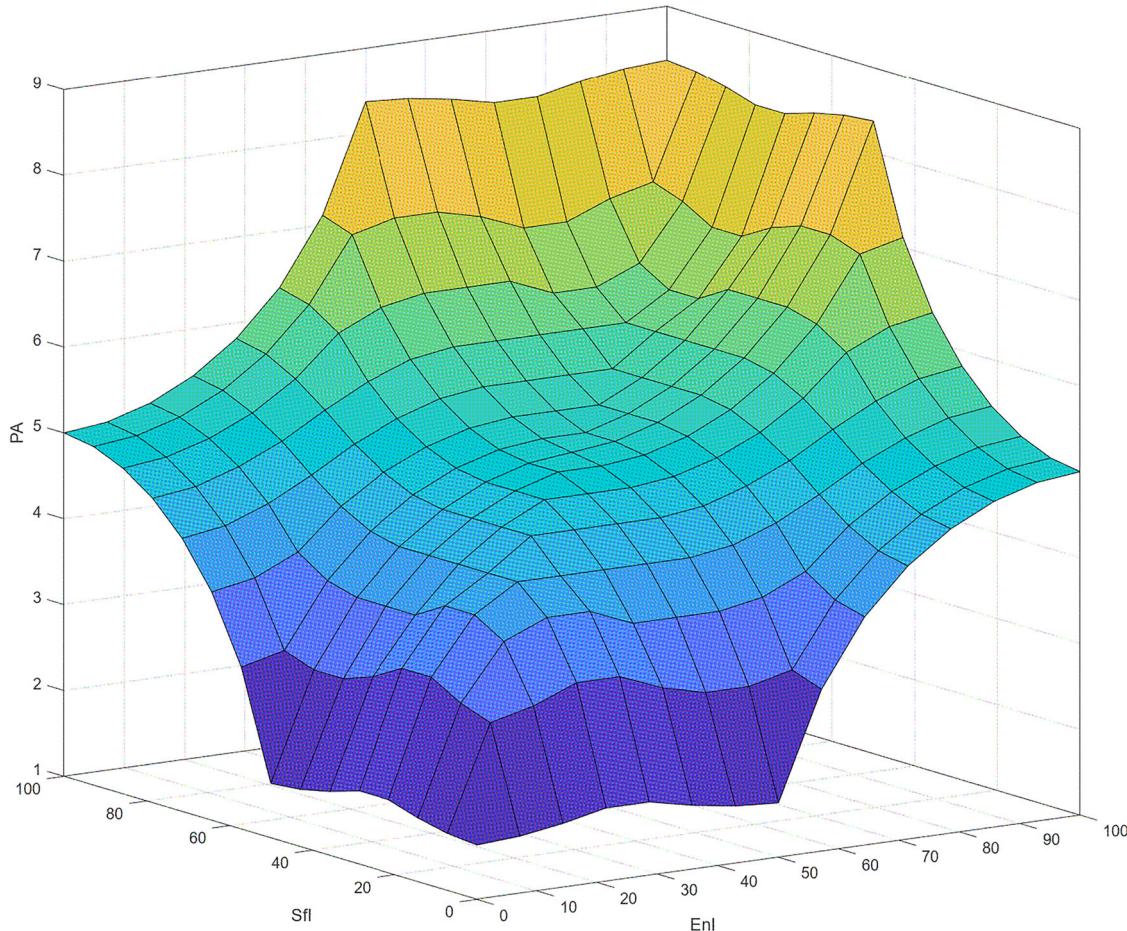


Fig. 9 Fuzzy surface of PA sub-model. The surface represents the relationships between SI, EI, and PA.

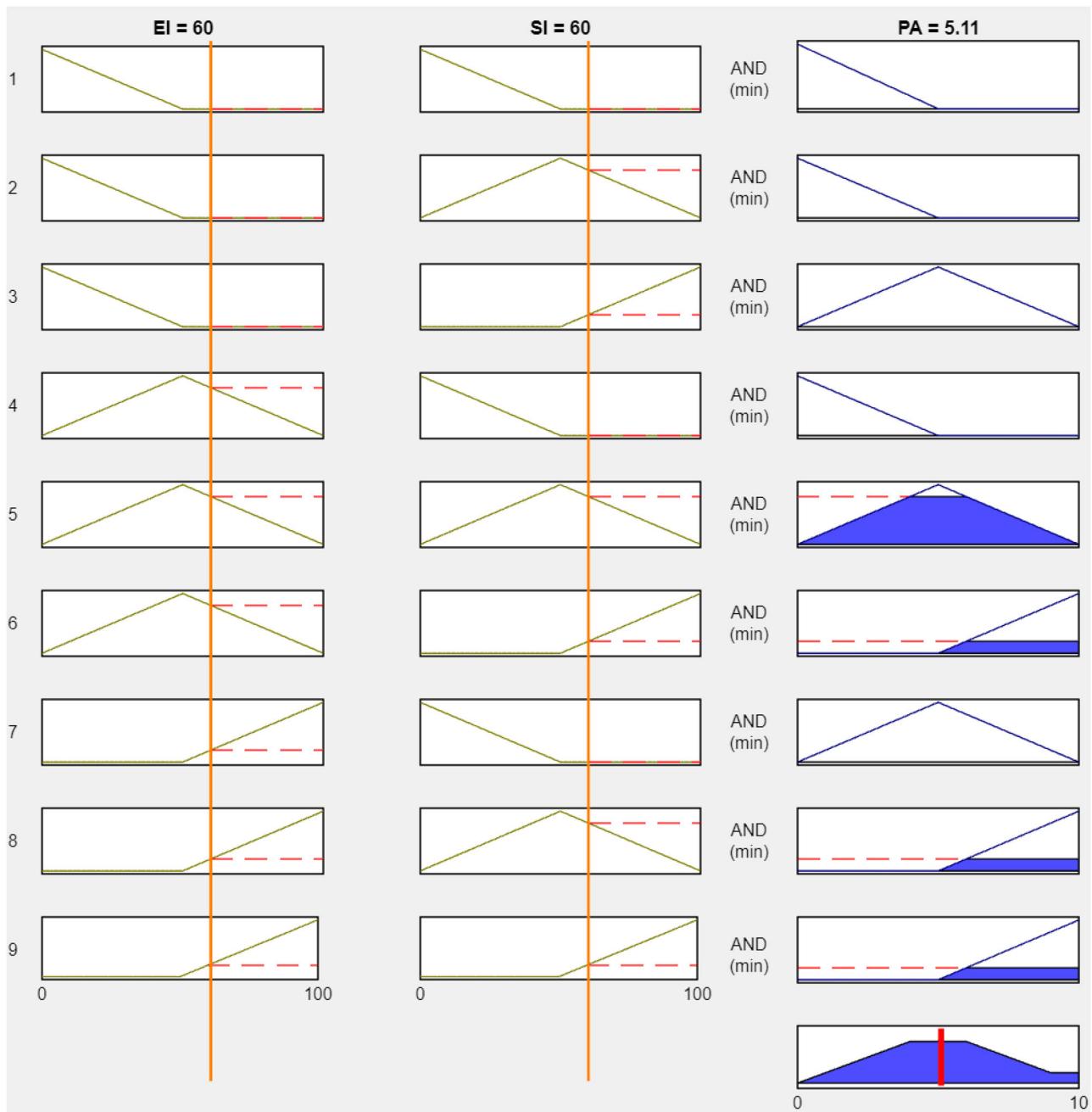


Fig. 10 Defuzzification process. The lines in the EI and SI represent the membership functions of fuzzy numbers; the blue parts on the right side represent the defuzzification results.

currently lacks a mandatory vessel navigation regulation, and the AIS data compiled in this study did not filter the vessels' headings, it is not possible to confirm if ships are sailing against the channel or crossing into the Offshore Wind Farm area. Finally, some Offshore Wind Farm areas have higher vessel density. Excluding workboats involved in offshore wind farm planning and construction, many vessels still navigate the offshore wind farm area. The channels must be replanned before construction in the third phase of future offshore wind farms.

Navigational warning area. This paper used the Fuzzy Logic Designer in MATLAB to calculate each sub-model of the multi-level FLC model. This study divides the offshore wind farm area into a grid based on a safe distance of 2 nautical miles between

two encountered ships. The grid cells were numbered from top to bottom and left to right, with the top-left grid numbered zero, and the bottom-right grid numbered 168, totaling 169 grids. This section uses the area adjacent to the Changhua Offshore Wind Farm channel (indicated by the red square in Fig. 12) as an example. Table 5 lists the extracted FLC calculation results.

Table 5 lists the score output by the FLC model on the corresponding grids in the MGIS. WF, HF, ES, NS, EI, SI, and PA mean wind factor, hydrological factor, ecological sensitivity, navigational safety, environmental index, safety index, and precautionary area. The scores for WF, HF, ES, and NS are from the first phase of the FLC model. The scores for EI and SI are from the second phase of the FLC model. The scores for PA are from the third phase of the FLC model. As a result, PA index

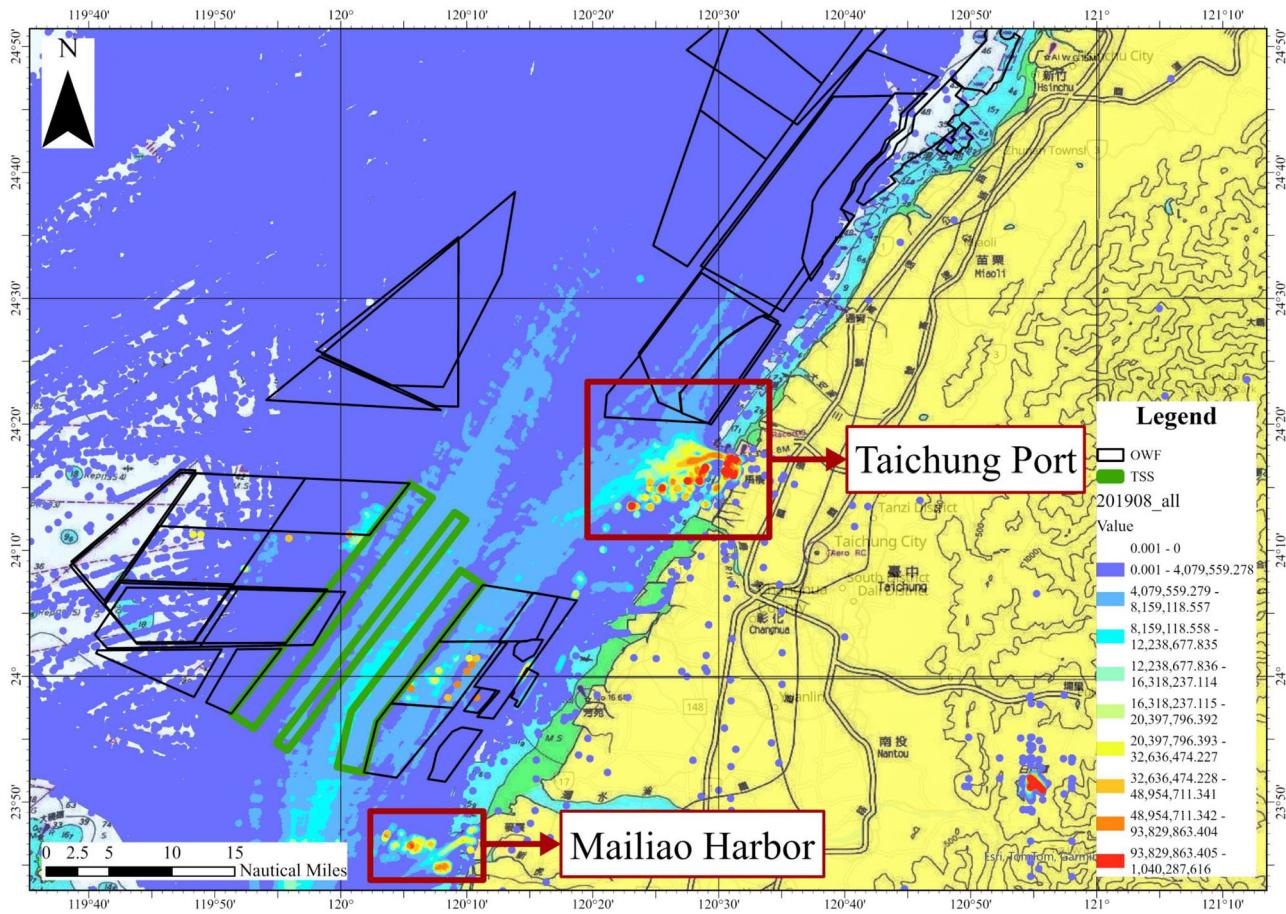


Fig. 11 Vessel traffic density map of the OWF area in Western Taiwan. The various colors in the figure represent the density of vessel traffic.

values ranged from 4.8673 to 5.1106, with an average score of 4.996, which served as the selection threshold. Grids with scores higher than the average were marked in blue, with darker shades indicating higher scores within the grid. Figure 13 showed the results. High-score areas are concentrated in the northern region and the southwest region near the Changhua Wind Farm channel. To prevent the model's output scores from becoming too convergent and affecting the research results, Min-Max Normalization was applied to scale the scores linearly between 0 and 10, without altering the original data distribution. To make the PA more complete, the normalized value of the average minus one standard deviation was used as the selection threshold, as shown in Eq. (11). This threshold setting helps to retain more grids while effectively eliminating outlier data caused by normalization (Reimann et al. 2005; Li et al. 2010). Finally, with 2.665 as the selection threshold, the results drawn on MGIS are shown in Fig. 14, where the grids marked in blue have scores higher than the threshold, with darker colors indicating higher scores in those grids.

$$\text{Threshold} = \text{mean} - \text{standard deviation} \quad (11)$$

By overlaying and comparing the output results of the FLC model, the normalized output results, and the original precautionary area, we can observe that the high-score regions concentrate in the southwest region near the Changhua Wind Farm channel and in the northern region. It indicates that these areas experience more vessel traffic, which requires more specific attention from the relevant authorities. Based on the multi-criteria precautionary area plan proposed in this study, and

compared to the original one, the region needs to be extended 2 to 6 nautical miles towards the north and strengthened in the southwest area near the Changhua Wind Farm channel to accommodate actual maritime traffic flow and environmental considerations. The foresight of PAs and channels must estimate OWF areas and ecological regions and promote adherence to relevant regulations to reduce collisions and foster the sustainable development of the maritime industry, the green energy sector, and the ecological environment.

Discussion. Although Taiwan has completed several offshore farms along its western coast, it has not yet fully completed all offshore wind farms. That is, Taiwan will build more offshore wind farms in the future. The analysis approach and the FLC model would be applied to other offshore wind farms to analyze the navigational risk. It is the operational management implications.

One of the challenges is that the AIS data used in this study is historic data rather than real-time data. To increase the efficiency of the analysis method, future studies could utilize real-time data to analyze real-time environmental conditions, providing real-time navigational risks.

Some typhoons visit the Taiwanese coasts every year. The typhoons not only cause damage to offshore wind turbines but also disrupt the navigational safety of vessels in the waters of offshore wind farms around the western coast of Taiwan. Therefore, future studies on analyzing navigational safety in offshore wind farms should consider weather conditions such as typhoons or heavy weather.

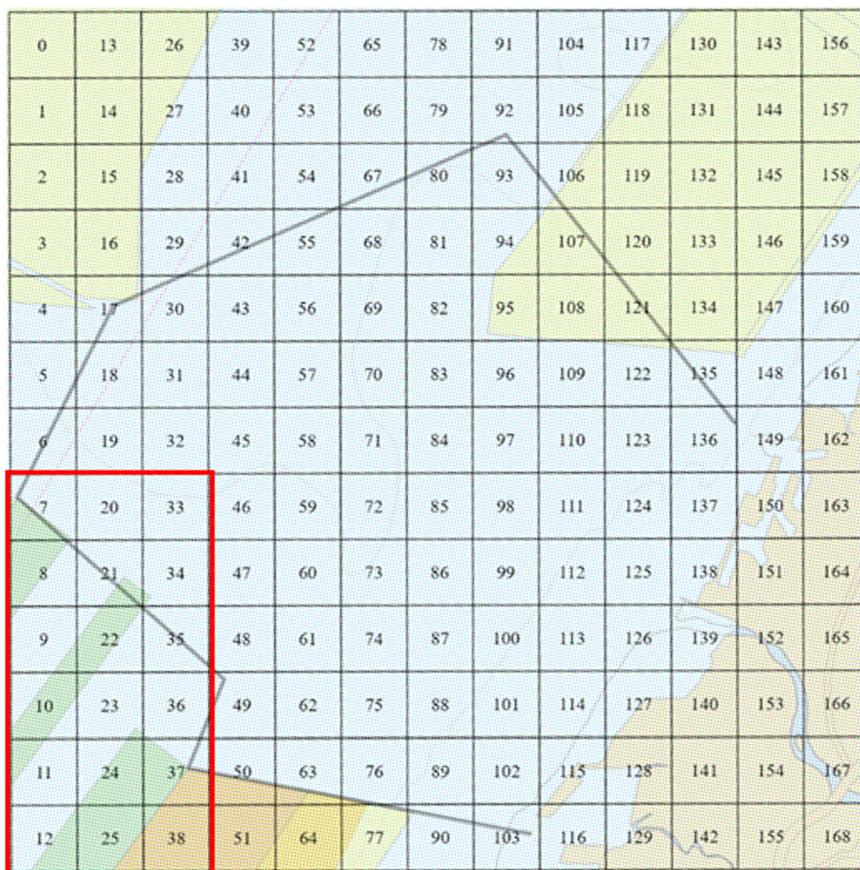


Fig. 12 Extraction range of example grids. The red square indicates the area adjacent to the Changhua Offshore Wind Farm channel.

Table 5 The score output by the FLC model.

Grid number	WF	HF	ES	NS	EI	SI	PA
7	41.642	49.836	55.026	34.907	49.265	48.458	4.9959
8	37.257	43.536	55.026	45.931	48.334	50.357	4.9961
9	30.700	16.509	62.857	49.982	39.517	60.605	5.0024
10	17.779	16.509	63.877	50.344	39.067	61.011	5.0016
11	30.261	17.133	63.887	50.063	40.034	61.291	5.0267
12	48.129	17.133	63.887	47.417	39.492	61.040	5.0106
20	41.425	49.836	55.026	49.362	49.228	51.054	5.0007
21	37.541	43.536	55.026	50.063	48.404	51.094	4.9980
22	29.967	43.536	63.887	50.466	46.017	61.222	5.1106
23	22.114	16.379	63.887	49.752	40.327	59.752	5.0014
24	30.483	43.536	63.887	45.084	46.215	60.637	5.0998
25	37.927	43.536	63.887	35.704	48.498	48.745	4.9960
33	41.812	50.224	55.026	50.499	49.330	50.052	4.9988
34	38.779	49.836	55.026	51.118	48.711	51.116	4.9993
35	22.796	43.536	55.026	49.979	42.613	50.000	4.9399
36	45.918	16.379	55.026	45.595	38.673	50.314	4.8673
37	47.364	43.536	54.990	23.295	49.843	44.373	4.9635
38	40.594	43.536	49.955	-	49.059	-	-

Conclusion

In recent years, Taiwan has actively promoted the development of OWF on the western coast. However, the planning process needs to balance multiple dimensions, including shipping, fisheries, and ecological conservation. This study aims to apply scientific methods to plan wind farm shipping channels and PA, ensuring the smooth advancement and sustainable development of offshore wind power.

Previous PA planning primarily considered vessel traffic density. However, this study incorporates sustainable development technologies as one of the factors, combining them with vessel traffic density to propose an alternative PA plan that considers multiple factors. This plan ensures both navigational safety and ecological conservation during the development and future use of OWFs, while also considering wind and hydrological factors.

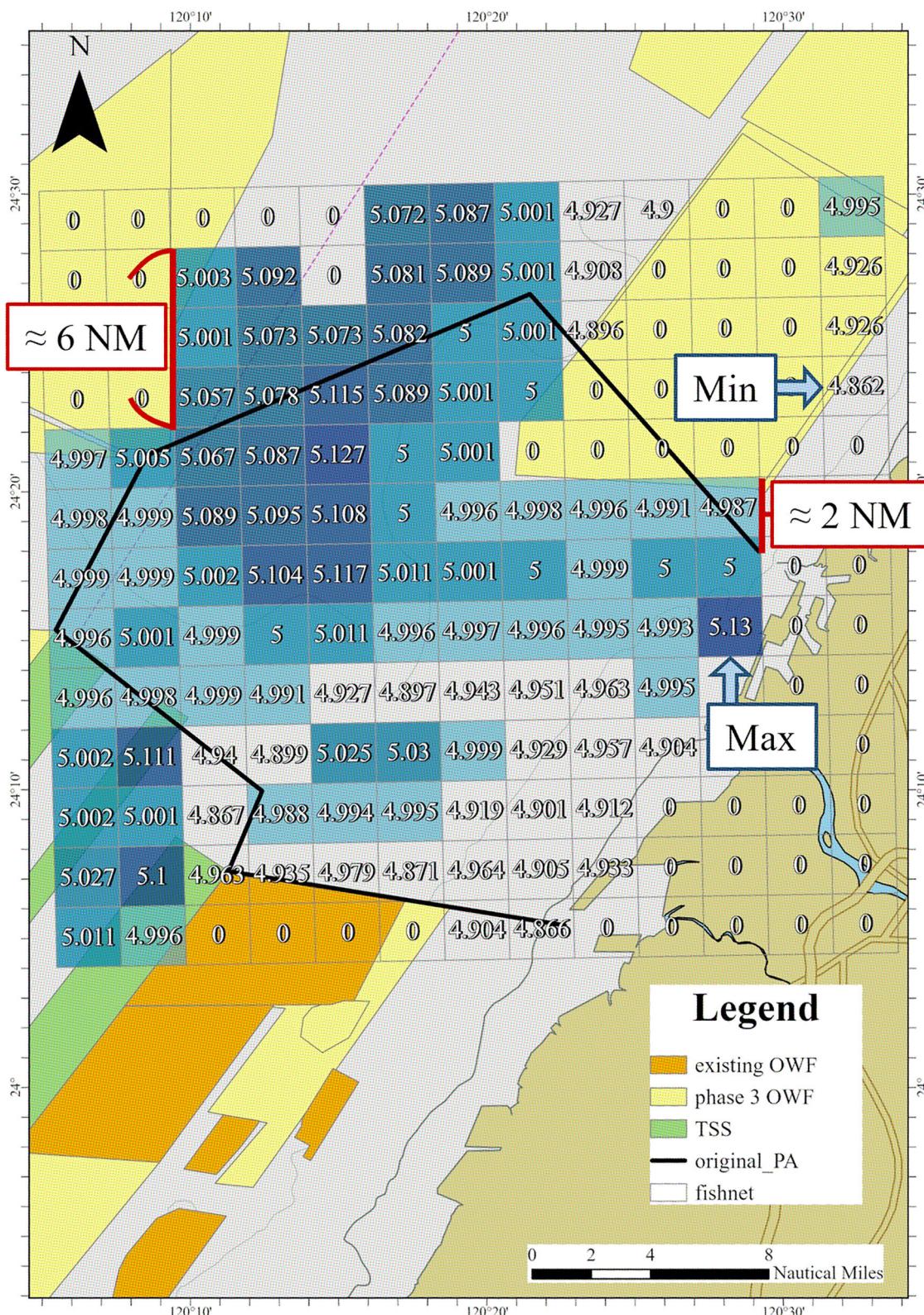


Fig. 13 The PA indicator value is output by the FLC model. The grids marked in blue have scores higher than the threshold, with darker colors indicating higher scores in those grids (before normalization).

This study first integrates AIS historical data with MGIS and maps the vessel traffic density distribution in the western OWF area of Taiwan. The vessel density is higher around Taichung and Mailiao harbors, with vessels primarily concentrated along the

northward shipping channel on the eastern side of the Changhua Wind Farm channel. Furthermore, some areas of the future third-phase wind farm still overlap with existing vessel traffic tracks, and future adjustments to shipping channels and

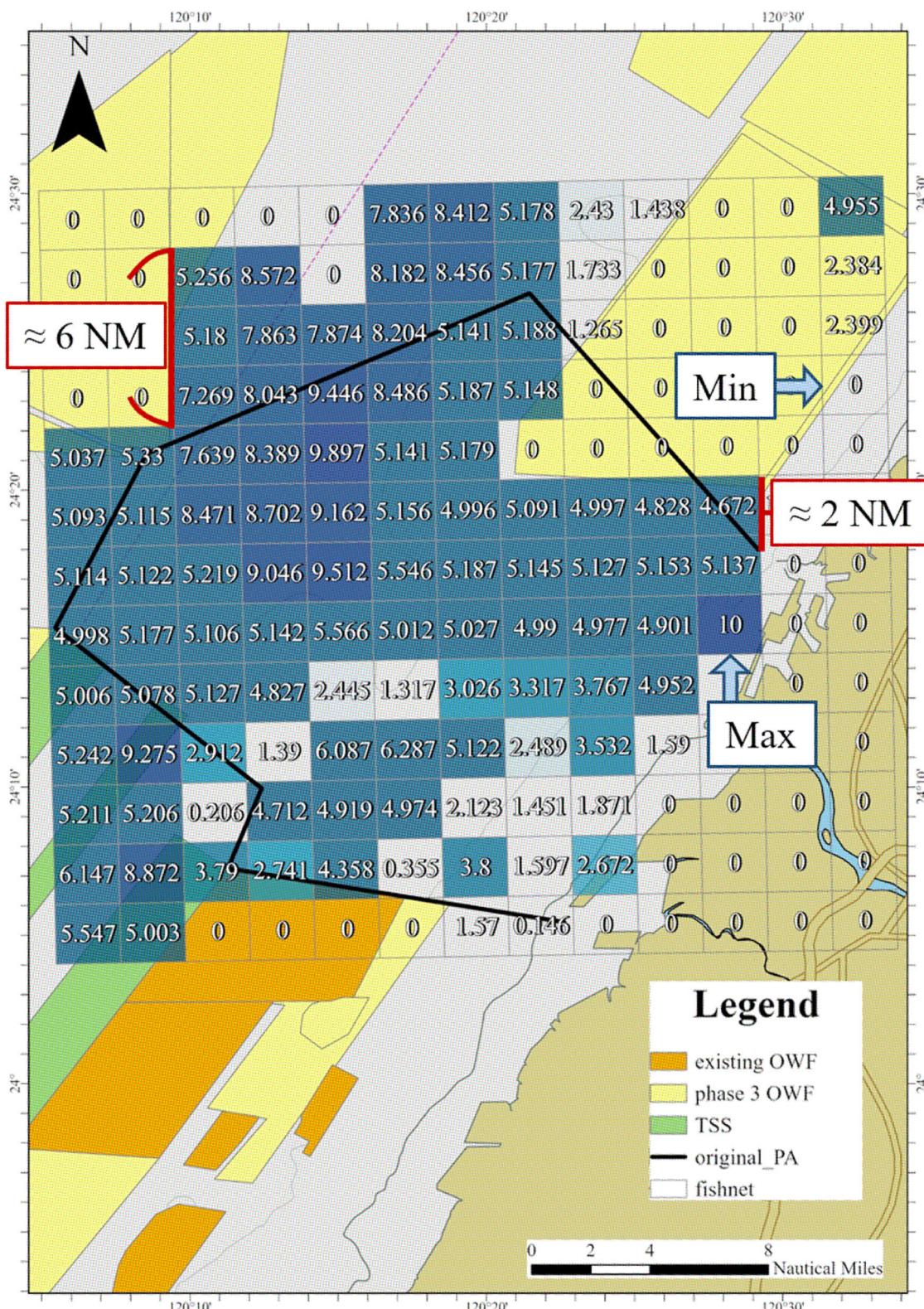


Fig. 14 The PA indicator value after normalization. The grids marked in blue have scores higher than the threshold, with darker colors indicating higher scores in those grids (after normalization).

PA will be required to balance wind farm and shipping demands.

To mitigate the impact of particular variables or factors on the ultimate calculation results, the FLC model in this paper treats all unprocessed information as equally important in its initial phase

without additional weights, and then calculates the PA indicator value. Additionally, this study employs min-max normalization to adjust the fuzzy output results and linearly scale the scores between 0 and 10 according to the original data distribution. Finally, the results are presented in numerical and color scale

formats overlaid on nautical charts in MGIS. The study results show that high-score areas in the precautionary area primarily concentrate in the northern region, as well as in the southwestern waters alongside the Changhua wind farm shipping channel. Compared with the original precautionary area, the proposed plan requires an extension of 2 to 6 nautical miles towards the north, focusing on managing the areas alongside the Changhua wind farm shipping channel, ensuring that the new precautionary area adapts to the development of Taiwan's OWF industry.

In the future, ships must strictly comply with relevant regulations, and maritime authorities and other industries operating in the sea areas must engage in complete and thorough communication and coordination. This collaborative effort will help build a safe maritime traffic network and promote the symbiotic development of the green energy industry, shipping safety, and the ecological environment in the OWF.

The proposed FLC model for PA planning in this study can be adapted for use in other ports or offshore wind farms worldwide by modifying data and parameters, such as traffic density, ecological environment, and hydrological conditions. This study contributes to academics and practice. Furthermore, artificial intelligence (AI) is a powerful tool and decision-making methodology that has been applied to various fields (Kao et al. 2020; Senapati et al. 2024; Senapati et al. 2025). Therefore, future studies could combine FLC and AI to solve the PA problems more efficiently.

Data availability

The data were available from the corresponding author on reasonable request.

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Author contributions

S-LK: Conceptualization, methodology, data curation. C-CC: Conceptualization, formal analysis, writing—original draft, and writing—review & editing. T-CL: Methodology, data curation, and writing—original draft.

Competing interests

The authors declare no competing interests.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors. Ethical approval was not required as the study did not involve human participants.

Informed consent

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Additional information

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