The Fuzzy Analysis of Western Windfarm Transportation Safety

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Abstract. The previously completed route planning research of Navigational Transportation Safety in the Taiwan Western wind farm analyzed delves into the expansion of sustainable wind energy and navigation safety together along the Taiwan Western for confronting the challenge of balancing resource coexistence and displacement. Previous studies primarily focused on route planning and vessel traffic density which developed the necessary comprehensive analysis. Therefore, this study examines the area of Taiwan's western Offshore Wind Farm (OWF) environmental issues to develop a Precautionary Area (PA) and RADAR handoff site location analysis. This model analysis introduces a new PA concept that considers navigational and ecological safety, and also wind and hydrological resources, and offshore RADAR handoff mechanisms. Automatic Identification System (AIS) and wind farm RADAR surveillance data are used for converting and analyzing information through the Marine Geographic Information System (MGIS) and Fuzzy Method (FM)that proposed an alternative PA and RADAR site location selection that could facilitate Taiwan's Green Energy and Navigational Safety.

Keywords. Wind farm RADAR, Precautionary area, AIS, MGIS, Fuzzy Method

1. Introduction

Navigational Transportation Safety and Green Energy efficiency are the key points in the Taiwan Western wind farm implementation. Taiwan accounts for 13.4% of this capacity [1]. With these limitations of island areas and the saturation of onshore wind farms, Taiwan focuses on developing offshore wind farm transportation routes and facing challenges such as channel compression and navigation safety issues [2][3]. Wind farm RADAR surveillance and Precautionary Area (PA) analysis are crucial for vessel navigational safety, ensuring timely guidance to prevent collisions. Effective control handoff between VTS (Vessel Traffic Service) stations in overlapping RADAR areas is essential [4]. Also, PAs are typically designated in areas with intricate traffic flow and collision rates on sufficiently high levels; therefore, vessels navigating with heightened

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caution are necessary [5]. Combining the PA with Wind Farm RADAR systems provides dual protection in high-risk areas. Previous studies used Fuzzy Methods (FM) [6][7][8] and AIS (Automatic Identification System) data for maritime route decision-making for specific applications. The PA and RADAR surveillance area planning will be the next steps and new projects. This study used the Fuzzy theory and the Marine Geographic Information System (MGIS) to integrate AIS data with sustainability criteria. PA planning and RADAR control handoff timing were analyzed for Taiwan's Western Wind Farm channels, addressing all the PA and RADAR overlap issues.

2. Methodology

2.1. Automatic Identification System

The AIS is an indispensable piece of navigation equipment essential for safe sailing. According to Regulation 19 in Chapter V of the International Convention for the Safety of Life at Sea (SOLAS), ships with a gross tonnage of 300 or more engaged in international voyages, cargo ships with a gross tonnage of 500 or more not engaged in international voyages, and all passenger ships must be equipped with an AIS. This regulation serves several key purposes: (1) provide information (including the ship's identity, type, position, course, speed, navigational status, and other safety-related information); (2) receive automatically such information from similarly fitted ships; (3) monitor and track ships; and (4) exchange data with shore-based facilities[9].

The AIS integrates a Global Positioning System (GPS) with a Very High Frequency (VHF) transceiver to broadcast essential navigation details of vessels, including their precise position, current speed, and navigational status. It utilizes two designated VHF channels: channel 87B (161.975 MHz) and channel 88B (162.025 MHz), facilitating dependable communications over distances of about 20 to 30 nautical miles. Required for most ships over 300 gross tonnes by the SOLAS Convention, the Class A AIS transceiver uses SOTDMA technology to ensure reliable communication within the AIS range. Integrating AIS data into the Electronic Chart Display and Information System (ECDIS) enhances maritime traffic awareness, helping prevent collisions.

2.2. Fuzzy Logic Control

Fuzzy theory was introduced by Lotfi A. Zadeh, a former professor at UC Berkeley, in 1965; fuzzy set theory and fuzzy logic were designed to address problems that traditional mathematical methods found difficult to define. These challenges spanned areas such as human cognition, the articulation of meaning, and subjective evaluation. Zadeh observed that the rigid logic of computers failed to adequately capture the nuances of human thought, which often includes vague or ambiguous concepts. Fuzzy logic, conversely, mirrors the human brain's approach to processing information more naturally. A typical fuzzy system consists of four main components: fuzzification, which translates real-world numerical inputs into fuzzy sets; a set of fuzzy rules; a fuzzy inference engine that applies these rules; and defuzzification, which converts fuzzy set outputs back into precise numbers[10][11].

Fuzzy theory expands binary logic into continuous multi-value logic, using a scale from 0 to 1 to denote an element's membership degree. The literature highlights a variety of curve shapes, yet triangular or trapezoidal membership functions are frequently chosen for fuzzy control systems. This study leveraged the Fuzzy Logic Toolbox in MATLAB to tackle challenges using fuzzy logic principles.

Defining fuzzy rules is a critical aspect of fuzzy control, involving a set of IF–THEN control rules described by semantics. The fuzzy inference engine primarily conducts an approximate inference based on rule-based settings[12][13]. The min-max inference method proposed by Mamdani is the most commonly used approach. Defuzzification's role is to quantify and convert the fuzzy inference result into the membership function value of the output variable. The Center of Gravity (COG) is the most widely adopted defuzzification strategy, as shown in formula (1).

$$y(x) = \frac{\sum_{i=1}^{N} yi \, \mu(yi)}{\sum_{i=1}^{N} \mu(yi)} \tag{1}$$

2.3. Marine Geographic Information System

Geographic Information Systems (GIS) have advanced significantly, utilizing computer technology to manage and analyze spatial data. Originally focused on land, GIS has expanded to encompass marine environments through Marien GIS (MGIS). MGIS combines four-dimensional oceanographic data to support diverse applications in fields like deep-sea geology, coastal engineering, and resource management, offering adaptable environmental insights.

GIS emphasizes organizing map elements in a stratified manner. The process of layer addition necessitates a thorough identification of the exact placement, orientation, and interrelations of adjacent objects. Visually, the system captures spatial information through various geometrical shapes such as points, lines, polygons, or raster images and distinguishes each entity within a layer using unique symbols.

3. FLC Model of Alternative PA

This study designed a three-stage FLC model (1) with two inputs for each stage. The first stage includes four sub-models: wind energy resources, hydrological resources, ecological security, and navigation security. The second stage consists of two inputs: Ecological Index and Safety Index. Finally, the third stage uses the outputs of the second stage to derive a main output—alternative PA.

First, AIS information is collected from the west coast of Taiwan, and ship parameters and geographical locations are obtained for fuzzy analysis. Other data come from government statistics.
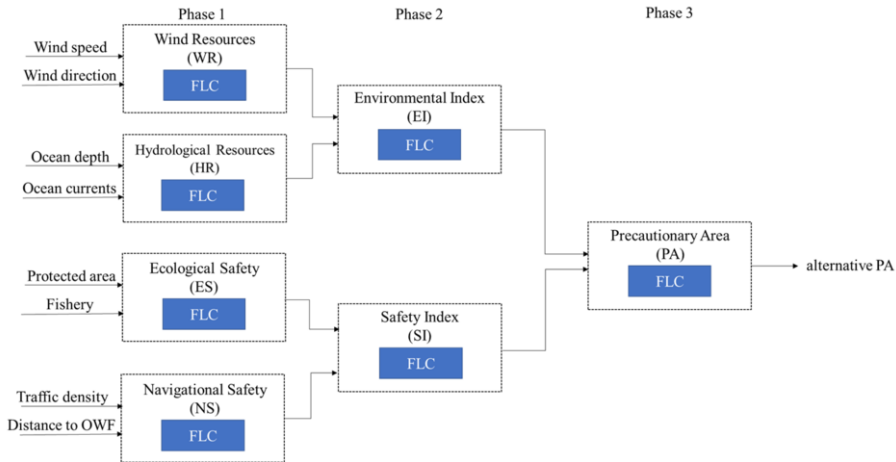
Figure 1. FLC model for alternative PA

3.1. Fuzzifier

MATLAB was utilized to determine the degree of fuzziness. For instance, during phase 3 of the FLC model, the Environmental Index (EI) and Safety Index (SI) were used as input variables, with PA being the final output.

Environmental Index (EI)

During sea voyages, ships are affected by wind, ocean depth, and ocean currents, which affect their trajectory stability and speed. Strong winds can compromise a tall ship's stability, and shallow water and adverse currents can limit speed. For safe navigation, careful planning is necessary. Therefore, the EI variable is divided into three membership function values. A language variable is set for EI, defined as 0, 50, and 100, respectively. EI contains three membership functions: bad, medium, and good. When the EI value is close to 0, it belongs to the function EI_{Bad}. When the EI value is close to 100, it belongs to the function EI_{Good}.

Safety Index (SI)

Ecological and navigational safety are crucial to ship operations. Ecological security protects marine ecosystems from pollution and maintains biodiversity and water quality. Navigation safety prevents accidents and deals with hazards such as traffic, navigational obstacles, and offshore construction. Implement measures to ensure both the protection of the environment and the reduction of risks at sea, promoting safety and sustainability. Therefore, the SI variable is divided into three membership function values. A language variable for SI is defined as 0, 50, and 100, respectively. Therefore, SI contains three membership functions: poor, medium, and good. When the SI value is close to 0, it belongs to the function SI_{Bad}. When the SI value is close to 100, it belongs to the function SI_{Good}.

Precautionary Area (PA)

The PA model was arbitrarily scored on a scale of 0 to 10. The relevant PA variable was set to be the semantic variable of PA, with three membership functions: Bad, Moderate, and Good.

3.2. Rule Base

The inference engine consists of IF-THEN statements that relate a given condition to an outcome. This study used EI and SI as inputs and PA as output and discarded 18 conflicting rules out of a total of 27 rules. The remaining 9 rules are shown in Table 1. Finally, this study aimed to develop an alternative PA model for additional ports in Taiwan as part of future research. The primary challenge encountered was collecting marine meteorological information, which proved difficult without government support and infrastructure. Despite the establishment of AIS websites and weather information through various sensors in Taiwan's international ports, significant adjustments are required for environmental and ship traffic density at other Taiwan ports. In subsequent studies, alternative PA models will be developed for different seasons in the western Taiwan wind farm area, followed by the creation of models for other ports in Taiwan.

Table 1. Rule base

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

3.3. Defuzzifier

Figure 2 illustrates the defuzzification process, a computational procedure employed to determine fuzzy logic output based on the aggregation result. The defuzzification process utilizes the COG method to compute the final solution.
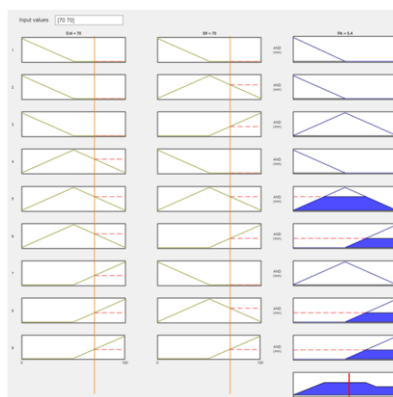

Figure 2. Defuzzification process

4. FLC Model of Control Index

This study designed a five-stage FLC model (Figure 3) with two inputs at each stage. The first stage includes three sub-models: turning capability, stopping capability, and sea surface wind current factors. The second stage includes two inputs: ship maneuverability and environmental influence. The third stage uses the output of the second stage to determine the Ship Maneuvering Capacity Index. The fourth stage uses the output of the third stage and Ship Type to determine the Vessel Route Right Index (VRRI). The fifth stage uses the output of the fourth stage and the Surveillance Distance Index (SDI) to produce a major output —the Control Index.

First, AIS information was collected from the west coast of Taiwan to obtain ship parameters and geographical locations for fuzzy analysis. Other data were sourced from government statistics.
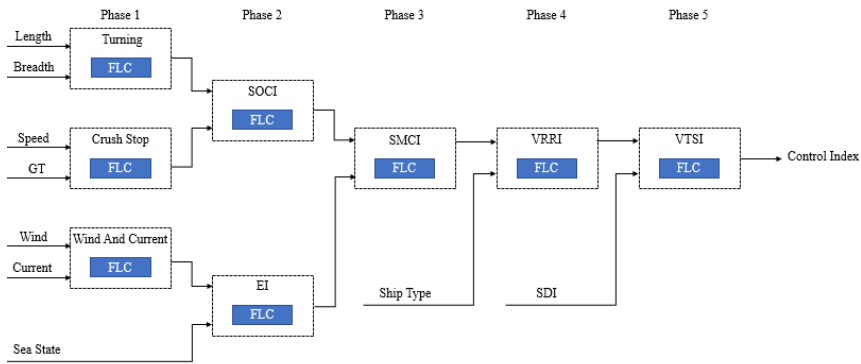

Figure 3. FLC model for Control Index

4.1. Fuzzifier

MATLAB was utilized to determine the degree of fuzziness. For instance, during phase 5 of the FLC model, VRRI and SDI were used as input variables, with the Vessel Traffic Surveillance Index (VTSI) being the final output.

Vessel Route Right Index (VRRI)

Scheduling and prioritizing vessels in busy waterways and port areas can significantly enhance navigational safety and efficiency. In congested channels, increased traffic density raises the risk of collisions, while the limited space and heavy traffic in port entry and exit areas lead to delays and accidents. Careful planning is essential for safe navigation.

The VRRI variable is divided into three membership function values to address this. A linguistic variable was set for VRRI, defined as 0, 50, and 100. VRRI includes three membership functions: Low, Medium, and High. When the VRRI value is close to 0, it belongs to the function $VRRI_{Low}$; when the VRRI value is close to 100, it belongs to the function $VRRI_{High}$.

Surveillance Distance Index (SDI)

The surveillance distance is a crucial indicator for measuring vessels' distance from VTS stations. By utilizing real-time RADAR to monitor the distance between vessels and VTS stations, it is possible to pre-plan the dynamics of surrounding vessels, ensuring safe navigation within controlled areas, preventing collisions, avoiding traffic congestion, and mitigating navigational hazards.

Thus, the SDI variable is divided into four membership function values. A linguistic variable for SDI was set, defined as 1, 9, 18, and 27. Consequently, SDI includes four membership functions: Immediate, Close, Medium, and Far. When the SDI value is close to 1, it belongs to the function $SDI_{Immediate}$. When the SDI value is close to 27, it belongs to the function SDI_{Far}.

Vessel Traffic Surveillance Index (VTSI)

The VTSI model is scored randomly on a scale of 0 to 10. The relevant VTSI variables are set as semantic variables of VTSI; there are three membership functions: low, medium, and high.

4.2. Rule Base

The inference engine consists of IF-THEN statements that associate given conditions with results. This study uses VRRI and SDI as input and VTSI as output and removes 24 conflicting rules from 36 rules. The remaining 12 rules are shown in Table 2. Although Taiwan's international ports have established AIS websites and weather information sensors, other ports' environments and ship traffic density require major adjustments. In follow-up research, VTSI models will be developed for different RADAR sites in the western Taiwan wind field area in Taiwan.

Table 2. Rule base

Rules	VRRI	SDI	VTSI
1	Low	Far	Low
2	Low	Medium	Low
3	Low	Close	Medium
4	Low	Immediate	Medium
5	Medium	Far	Low
6	Medium	Medium	Medium
7	Medium	Close	Medium
8	Medium	Immediate	High
9	High	Far	Medium
10	High	Medium	High
11	High	Close	High
12	High	Immediate	High

4.3. Defuzzifier

Figure 4. illustrates the fuzzy understanding process. The defuzzification process calculates the final solution using the COG method.
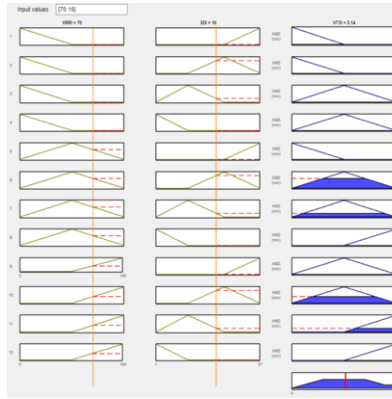

Figure 4. Defuzzification process

5. Result

Previous route planning research for Navigational Transportation Safety in the Taiwan Western wind farm proposed the navigation routes and was published by the Ministry of Transport, following the mission depicted in Figure 5.
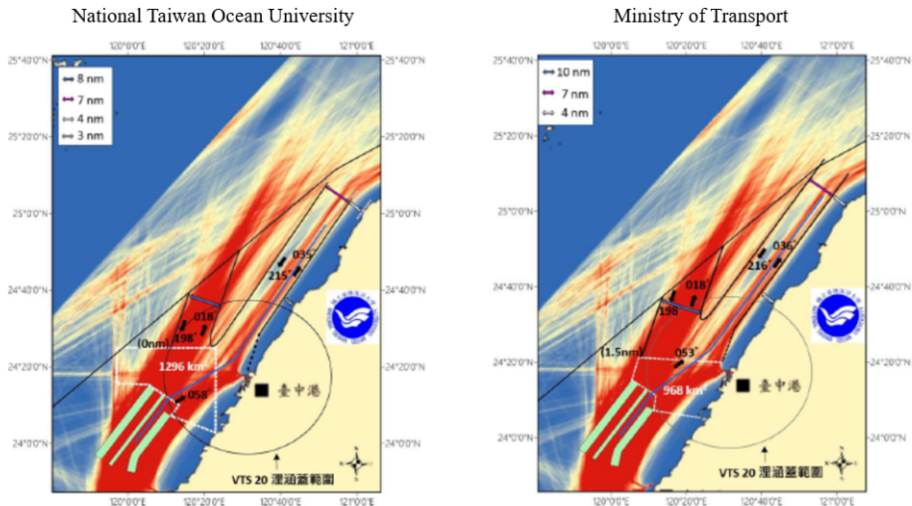

Figure 5. Previous Route planning research

    In this PA study, all raw data within the fishnet grid (169 grids) were calculated using the FLC model. Except for the PA sub-model, scores for other sub-models range from 0 to 100, with higher scores indicating more favorable conditions for vessel navigation. The scores for the PA sub-model range from 0 to 10, with higher scores indicating that the area may have more vessel traffic and should be designated as a Precautionary Area.

    After incorporating the final scores of the PA sub-model into the corresponding grid numbers, grids with scores below 4.9 were filtered out and finally imported into MGIS, as depicted in Figure 6(a). Comparative analysis with the government-recommended PA (black lines area) based on the study results revealed the necessity of extending the PA northward by 2-6 nautical miles to better align with the actual maritime traffic flow and environmental factors during the summer season. Future navigation planning and regulations must consider offshore wind farms and the precautionary area to adjust shipping lanes, align vessel traffic density with planned routes, and diligently avoid navigation within OWF and exclusion zones to mitigate collision risks.

    Another study adjusted and optimized the control ranges of the Taichung RADAR station and the Jin-Shui RADAR station to address overlapping conflicts and ambiguous jurisdiction issues in traditional monitoring ranges, thereby enhancing monitoring efficiency. The results showed that the Taichung RADAR station, having a higher control index, gained more control in the overlapping areas. In contrast, with a lower index, the Jin-Shui RADAR station had a smaller control area, which was finally imported into MGIS, as depicted in Figure 6(b). We derived the Vessel Traffic Control Index by applying FL to calculate the route weights and monitoring distance indices for each ship within the dashed-line area. After summing these indices, we redistributed the overlapping areas to optimize the monitoring ranges and reduce the extent of the overlapping areas (green area). These results indicate that the overall monitoring range of the RADAR stations has been significantly enhanced, effectively reducing monitoring blind spots and achieving more comprehensive and precise maritime traffic management. Such adjustments improve monitoring efficiency and provide valuable experience and references for future upgrades of monitoring systems.

(a)   (b)

Figure 6. Alternative PA and Control Index shown on MGIS

6. Conclusion

This study explores maritime traffic management and sustainable wind energy development in Taiwan's western OWF PA. Addressing resource coexistence and displacement proposes a new PA model that considers navigational and ecological safety alongside wind and hydrological resources. The FLC model calculated raw data within fishnet grids, filtering out scores below 4.9. The proposed extended PA aligns better with maritime traffic and environmental factors. Integrated into the MGIS, it aids future navigation planning. Control ranges for Taichung and Jin-Shui RADAR stations were optimized, reducing conflicts and enhancing monitoring. These findings highlight advanced analytical techniques in optimizing RADAR monitoring and maritime traffic management, offering valuable insights for future system upgrades.

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