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Investigation on Improving Strategies for Navigation Safety in the Offshore Wind Farm in Taiwan Strait

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Abstract: The Taiwan Strait, to the west of Taiwan, is rich in wind energy resources and has the greatest offshore wind power potential in the world. Therefore, Taiwan has been actively expanding its offshore wind power industry in this area in recent years and expects to achieve the total installed capacity to 15.6 GW by 2035. Due to the large vessel traffic flow in Western Taiwan's sea area, wind farms will inevitably reduce the navigable space and shadow some existing marine aids to navigation, thus worsening navigation safety. An approach using a fault tree analysis was used to carry out analysis of collision risk between ship-to-ship and ship-to-turbine. The vessel density distribution and traffic flow within the open sea of offshore wind farms would further increase to curtail the available navigable space. The shadowing effects along navigation channels would thereafter be worsened to raise the probability of collision risks in the sea. The results of the fault tree analysis revealed that if the ship is out of control, the time allowed to provide assistance is rather short, leading to the increase of collision risk extent between ships and wind turbines. Moreover, the study also found that unfit functions of the Vessel Traffic Service System and navigation aids and frequently and arbitrarily crossing the navigation channel of fishery vessels are the main causes of ship collisions. In order to effectively improve the navigation safety, competitive strategies for navigation safety are investigated and evaluated in this study. These strategies include making a complete plan for utilizing the whole sea, integrating the offshore vessel traffic service and management system, providing remote pilotage services, and building salvage vessels. The above promising strategies would enhance the navigation safety within the open sea. Collision risk might occur once marine accident occurs and no salvage vessel is available.

Keywords: navigation safety; offshore wind farm; strategy evaluation; Taiwan strait; vessel traffic service system

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1. Introduction

Wind energy is an important carbon-free renewable energy and one of the fastest-growing and cleanest sources of electricity in the world today [1]. The concept of offshore wind power was proposed in the 1930s. The world's first offshore wind farm was built in Vindeby, Denmark, which started the development of offshore wind farms globally [2]. In the 21st century, the installed capacity of offshore wind farms has increased from 1% of the global installed wind power capacity in 2009 to more than 10% in 2019 [3]. The total global capacity of operating offshore wind farms exceeded 32 GW in 2020. Under the threat of COVID-19, the global installed capacity of offshore wind farms still exceeded 5.2 GW in 2020 [4]. In terms of construction technology, floating wind turbines have been built in water 175 m deep away from the coast of Peterhead in Scotland, breaking the 60-m water depth limit for wind turbines of foundation pile type [5]. However, as deep sea is usually far away from shores, it is more expensive to build such floating wind turbines.

Taiwan, located in the subtropical region of East Asia, is 393 km long and 145 km wide, with southwest winds prevailing in the summer (from May to October) and northeast

winds in the winter (from November to the next April) [6,7]. Taiwan lies in north–south direction, separated from the Chinese mainland to the west by the Taiwan Strait, which is about 100 nautical miles wide and faces the Western Pacific Ocean in the east. Taiwan's western coast is rich in wind energy resources, with stable and high wind speeds. Based on Taiwan's average annual wind power density at 80 m above sea level, there is at least 200-W/m^2 wind energy potential (Figure 1) [8]. Meanwhile, the wind energy potential of Taiwan's eastern sea is relatively low [9]. Since the water is hundreds of meters deep in the eastern sea, Taiwan's offshore wind farm development is currently concentrated in the western sea.

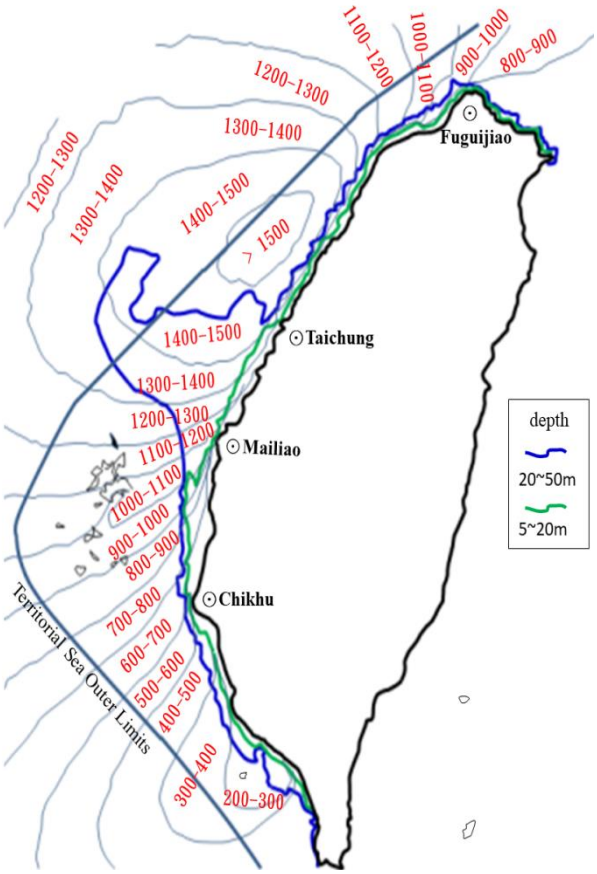

Figure 1. Distribution of the wind power density (W/m^2) in the ocean region close to Taiwan's western coasts. Source: plotted by the authors based on the data in Reference [8].

According to the observation of the world's average wind speed in 23 years, 16 of the world's top 20 wind farms are located in the Taiwan Strait [10], indicating that the western sea of Taiwan's own abundant wind energy resources has great potential for building offshore wind farms. However, it is noteworthy that not all of Taiwan's western sea is adequate for such development. According to Figure 1, the sea area is located from the northernmost point of Taiwan (Fuguijiao) to the southernmost point (Chikhu), with a water depth of less than 50 m and the average wind power density being more than 600 W/m^2 or even more than 1500 W/m^2, making the water area the best sea for wind energy development. Although some parts of the northern sea are 60–80 m deep, the difficulty of establishing wind farms can be overcome technically. Figure 1 shows that the shallow water area with a water depth of 5–20 m has a potential wind energy of 9 GW, the water area with a depth of 20–50 m has a potential wind energy of 48 GW, and the deep water area with a depth of more than 50 m has a potential wind energy of 90 GW [11].

Moreover, 76 out of the top 100 offshore wind farms based on the ranking of global offshore wind speeds among total 2122 wind farms planned for developing in 53 countries

are located in Taiwan [12]. In particular, the sea area from Fuguijao in the north to Mailiao in the middle of Taiwan attracts international large wind farm developers, including the Green Investment Group Limited (Scotland, UK), JERA Energy Limited (Chuo-ku, Tokyo, Japan), Northland Power Inc. (Toronto, ON, Canada), Ørsted A/S (Fredericia, Denmark), and WPD AG (Bremen, Germany), to actively invest and engage in planning and establishing offshore wind energy facility in recent years. However, the external wind force affects vessel navigation, and the ocean wave height is roughly proportional to the wind speed [13]. In addition, the effects of wind, waves, and ocean currents on wind turbines cannot be ignored [14,15]. A catastrophically structural failure of vessels or wind turbines might result from microstructure damage caused by a collision or wave attack onto those structures [16]. Odijie et al. [17] found that high stress distribution around the joint area of the inner column of a vessel hull under extreme weather conditions might be developed, leading to damage of the vessel structure. A real-time monitoring system can be developed by incorporating data such as wind, current profiles, or vessel motion to prevent unexpected accidents [18]. According to the research statistics, seven to eight typhoons hit the sea of Taiwan every year on average [19]. Such excessively strong winds might not only make offshore wind turbines fail to run but also cause damages [8,20]. In August 2015, Typhoon Soudelor damaged six onshore wind turbines in Taiwan [21]. If offshore wind turbines are damaged, it will even threaten navigation safety.

A total of 98% of Taiwan's primary energy source depends on imported energy [22]. With its west coast's great wind energy potential, Taiwan has actively promoted the wind energy development policy to meet the challenges of the gradual exhaustion of fossil fuels and the intensification of the greenhouse effect in recent years. The total installed capacity of offshore wind farms in Taiwan is estimated to reach 5.6 GW by 2025 and 15.6 GW by 2035. If the current 8-MW mainstream wind turbine is used, there will be about 1950 wind turbines in the western sea of Taiwan by 2035. All the offshore wind turbines will be built in the territorial sea and internal sea from Mailiao in the middle of Taiwan to Fuguijiao in the north (Figure 2). Such a large number of offshore wind turbines must have great effects on navigation safety in this area.

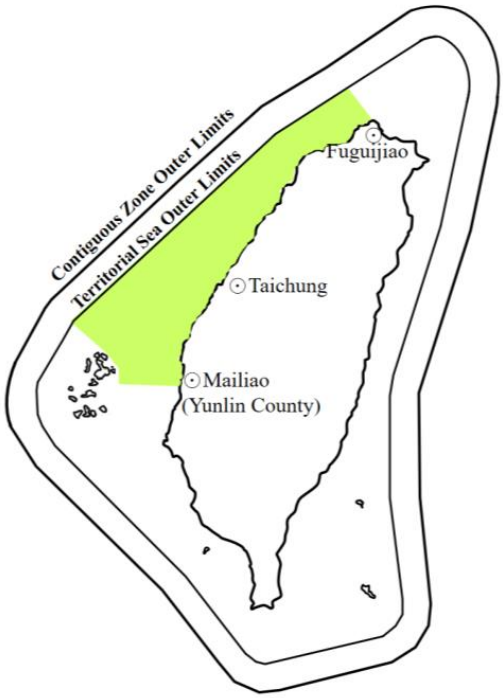

Figure 2. Schemed ocean regions marked in green for establishing offshore wind farm in the Taiwan Strait by 2035. Source: plotted by the authors.

Previously, most studies on Taiwan's offshore wind farms mainly focused on wind energy potential and wind turbine technology, while only a few studies tackled the effects of offshore wind farms on navigation safety and their coping strategies [21]. Chang et al. [23] evaluated the effects of offshore wind farms on the vessel traffic in the Penghu channel using the Automatic Identification System (AIS) data and suggested establishing navigation channels in Taiwan's offshore wind farms. However, their study only investigated the possibility of collision between vessels and wind turbines. In addition, Yu et al. [24] proposed that the vessel traffic flow and the distance between offshore wind turbines are the most important factors affecting collision risks between vessels and offshore wind turbines. Further, Yu et al. [25] collected AIS data before and after installing offshore wind farms to evaluate the effects of offshore wind farms on marine traffic flow. However, there has been no study on the overall strategy assessment of navigation safety in offshore wind farms [21]. Hence, the effects of offshore wind farms on navigation safety in the planned sea are investigated, and effective strategies to enhance navigation safety within offshore wind farms in western sea of Taiwan are developed in this study.

The outline of this study is stated as follows:

- Introduction: Briefly describe Taiwan's offshore wind farm policy and environmental profile.
- Establishment of traffic flow management in navigation channel within offshore wind farms: Conduct structured interviews with five captains who have sailed more than 50 voyages in the western sea of Taiwan.
- Risk analysis in a navigation channel within offshore wind farms: Qualitative analysis of the navigation risk using the fault tree analysis method and Boolean algebra.
- Influencing factors for navigation safety within offshore wind farms: Discuss the influencing factors for navigation safety.
- Developing promising strategies to improve navigation safety in wind farms: Promising strategies for promoting navigation safety are developed.
- Conclusions: Summarize the main results derived from this study.

2. Establishment of Traffic Flow Management in Navigation Channel within Offshore Wind Farms

2.1. Planning of Navigation Channels within Offshore Wind Farms

The foreign trade of Taiwan mainly depends on international shipping. Hence, vessel traffic in sea around Taiwan is frequently busy. Its western sea is an important route between Northeast Asia and Southeast Asia, with about 30,000 vessels sailing through this area every year [26]. Offshore wind farms not only greatly reduce the possibility of multiple sharing in a specific sea but also undoubtedly act as obstacles to navigation routes. Thus, to achieve the win–win goal of navigation safety and maximum offshore wind farm development, it is necessary to draft adequate policy to manage navigation effectively. Furthermore, in many countries, offshore wind farms are built in shallow sea near the shore, so that ships sail in the deeper sea outside the offshore wind farms, and the navigation space of ships is less limited. However, the open sea outside the middle of Western Taiwan is the key area for offshore wind farm development, as shown in Figure 2. The north–southbound area of the sea, close to the navigation channels to and from nearby international harbors and industrial ports, is usual route for vessels in the western sea of Taiwan. Fourteen potential offshore wind farm development sites have been planned in the sea [7], shown in Figure 2, and are built on the east and west sides of the north–southbound usual navigation route. This means that the navigation channels are established within the offshore wind farm region. As a result, ships can only navigate in a limited space channel with wind turbines on the left and right sides.

In order to ensure the order and safety of the north–southbound navigation channel, the buffer zone shown in Figure 3 [27] applies not only to the navigation in the north–southbound channel but also to the navigation of any fishing vessel, working vessel for offshore wind farm, and merchant vessel with a total tonnage of less than 300. Moreover,

the traffic flow of the vessels entering and leaving the navigation channel is complex and difficult to predict. Thus, it is planned as a precautionary area to remind vessels to keep their attention at all times. In addition, for traffic management of this water area, a Vessel Traffic Service System (VTS) has been planned to be established for the offshore wind farm outside the middle of Western Taiwan to manage navigation. Moreover, all vessels crossing and sailing along the channel within the wind farm region shall be installed with an Automatic Identification System (AIS), Very High Frequency (VHF), and radio equipment specified in the Global Maritime Distress Safety System (GMDSS) for navigation in A1 and A2 Seas, which has correctly set information and is turned on during the whole course. Vessels must submit their data before entering the channel and actively report to the VTS of the sea upon arrival [27]. In addition, to avoid collisions between vessels and offshore wind turbines during navigation, all offshore wind farms must specify safety areas, establish marine aids to navigation, and take appropriate measures to improve navigation safety, according to the governmental regulations [28].

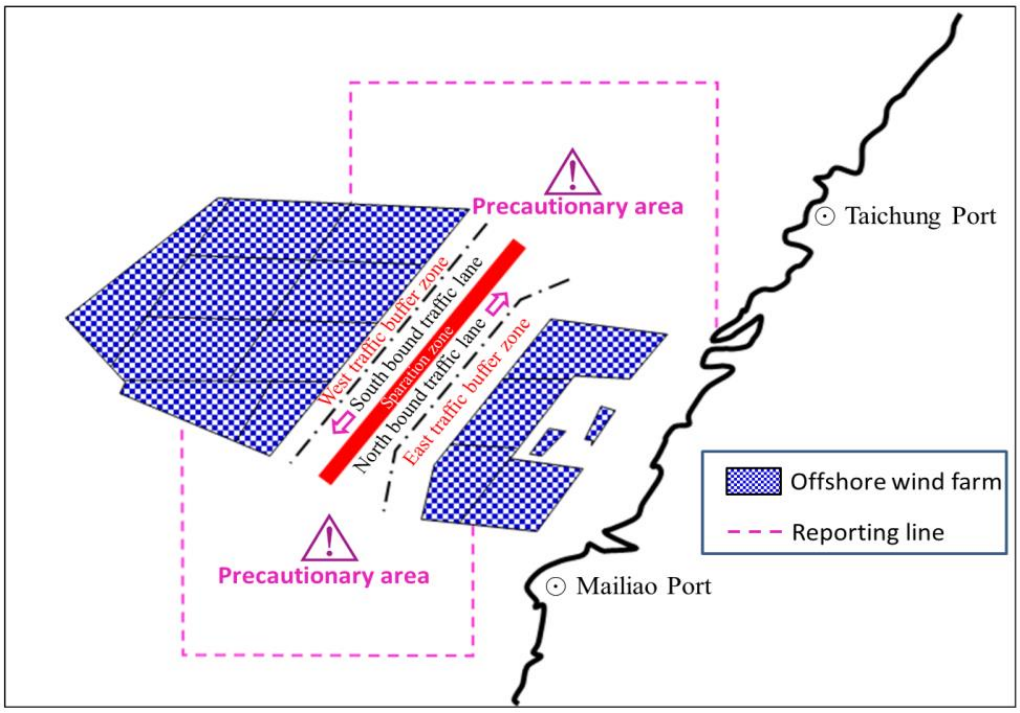

Figure 3. Specified navigation channel of the offshore wind farm close to middle of Taiwan's west coast. Source: plotted by authors based on the data in Reference [27].

2.2. Controlling for Fishing Vessel within Offshore Wind Farms

As offshore wind farms reduce the fishing and navigation space for local fishing vessels, it brings about adverse effects on fishermen's incomes. On the other hand, this authority may block the usual routes to fishing areas and greatly change the fishing vessel's existing operation and navigation model [6]. Consequently, fishermen may have to find another fishing area to capture fishes, which will not only increase the navigation risks for fishing vessels but also interfere in the navigation route of merchant vessels sailing in the western sea of Taiwan. In practice, offshore wind power developers allow fishing vessels to enter offshore wind farms for fishing, including permitting fishing vessels to cross their offshore wind farms to reduce their compensation for the fishing industry. The United Kingdom is the country with the most offshore wind farms, which generated electricity accounting for about 33% of the world's electricity from such an energy type in 2019 [3].

The authority of offshore wind farms of the United Kingdom considers that commercial fishing activities can be carried out in the limited sea of offshore wind farms. Limited fishing activities can be allowed in the specified sea of offshore wind farms, which is the

ocean region outside the protection areas with a radius of 50 m set around all wind turbines to keep off fishing vessels [29]. After examining the AIS monitoring data of the wind farms in the middle of the Western Taiwan coast, it revealed that a large number of vessels regularly enter open sea of wind farms (Figure 4) [30]. In addition, if small local fishing vessels or rafts without AIS are included, the situation of vessels crossing offshore wind farms is rather frequent, indicating that the measure that vessels are allowed to enter or cross wind farms taken in the offshore wind farms in Taiwan is similar to the practice in the United Kingdom. Therefore, the same control regulations for fishing vessel are expected to be applied to other offshore wind farms to be built in the future in Taiwan or other relevant countries.

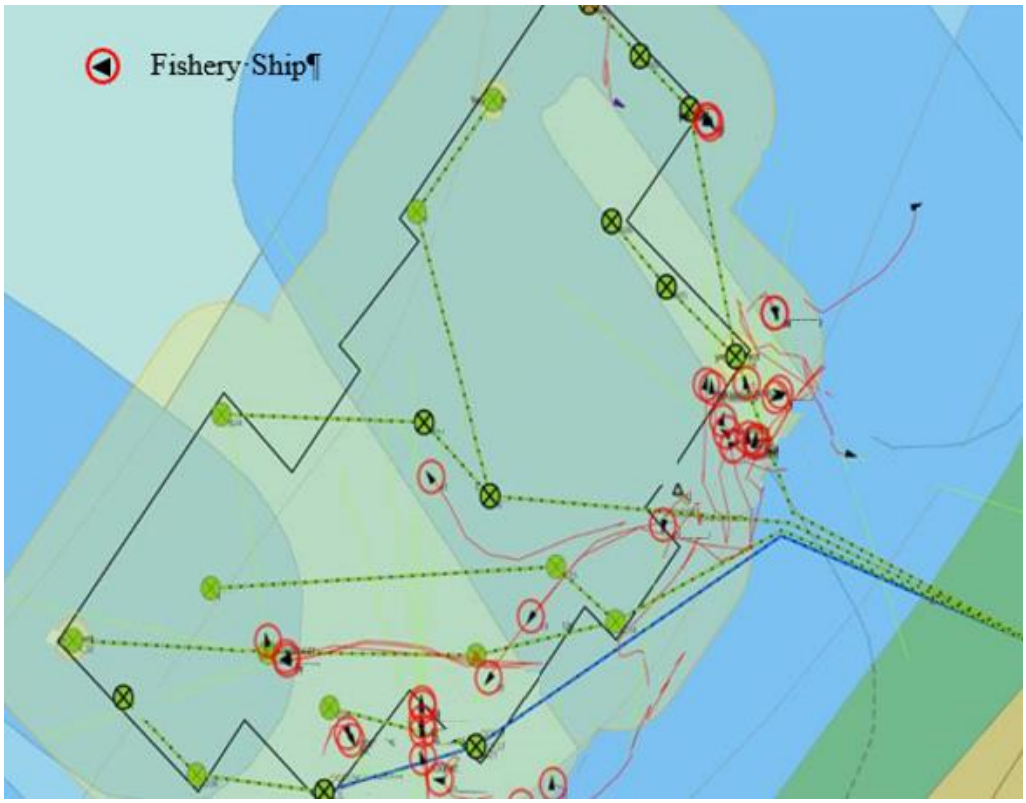

Figure 4. Tracks of fishing vessels in the offshore wind farm in the Central Taiwan Strait close to west coast of Taiwan based on AIS data. Source: based on the information in Reference [30].

3. Risk Analysis of Navigation Channel within Offshore Wind Farm

The establishment of offshore wind farms inevitably causes changes in the navigation environment. A fault tree analysis of a qualitative analysis for the possible risks in the navigation channel within the offshore wind farms was carried out in this study.

The fault tree analysis (FTA) is a well-established and well-understood technique, widely used to determine system dependability [31]. Fault tree graphics are generally plotted to analyze the logical relationship between faults and their causes. In the fault tree (Figure 5), basic events are represented by circular symbols that are the causes of top events, and intermediate events are represented by rectangles. In the implementation of the qualitative analysis of the fault tree, Boolean algebra is used. Hence, in the fault tree graph, there will be logical elements of AND gate (i.e., intersection, represented by ∩) and OR gate (i.e., union, represented by ∪). The intersection is equal to the product of the two sets while, and the union is the sum of the two sets [32], as shown in the following equations:

$$T = (R \cap Y) = R \,.\, Y \quad (1)$$

$$Y = (Z1 \cup Z2) = Z1 + Z2 \quad (2)$$

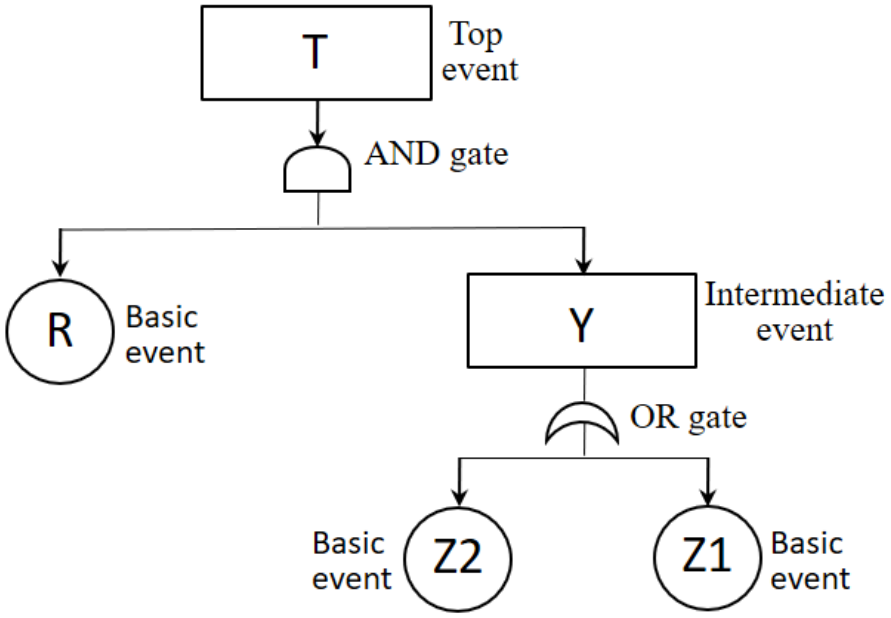

Figure 5. Structure of a fault tree.

The navigation risks caused by environmental changes due to the construction of offshore wind farms are analyzed. In order to obtain the analysis data, five senior captains with more than 50 voyages of experience navigating in the western sea of Taiwan were interviewed. According to the opinions of the five interviewed captains, collisions, including ship collisions with wind turbines and ship-to-ship collisions, are the most likely risk. In order to perform a fault tree analysis, the possible risks or events provided by these captains are randomly coded in Table 1.

Table 1. Events and codes of FTA for risks in the navigation channel within the offshore wind farm.

Codes	Events	Codes	Events
A	Collision	H2	Turbines on both sides of the channel
B1	Ship collided with turbines	J1	Incomplete situational awareness
B2	Ship and ship collision	J2	Difficult to navigate
C!	Ship drifting	K1	Disturbed lookout
C2	Invalid salvage	K2	Limited external environment
D1	Ship out of control	K3	Lack of assistance
D2	Current effect	L1	Turbines shadowing effects on channel
D3	Ship operation failed	L2	Fishery ships frequently cross the channel
E1	Machine failure	L3	Fishery ships crosses the channel between the turbines
E2	Propeller twist	M1	Heavy traffic
F1	Insufficient salvage response time	M2	Avoidable space is reduced
F2	Lack of a proper salvage Ship	N1	VTS is not functional
G1	Ship too close to turbines	N2	Defects in navigation aids
G2	The salvage ships too far away	P1	The channel has a large flow of ships.
G3	No salvage ships	P2	High ship density distribution
H1	Navigable space is limited to the channel		

By conducting the correlation analysis between the results and causes of the events in Table 1, the fault tree graphs in Figures 6 and 7 for analyzing the collisions of ships with wind turbines and ship-to-ship, respectively, can be obtained.

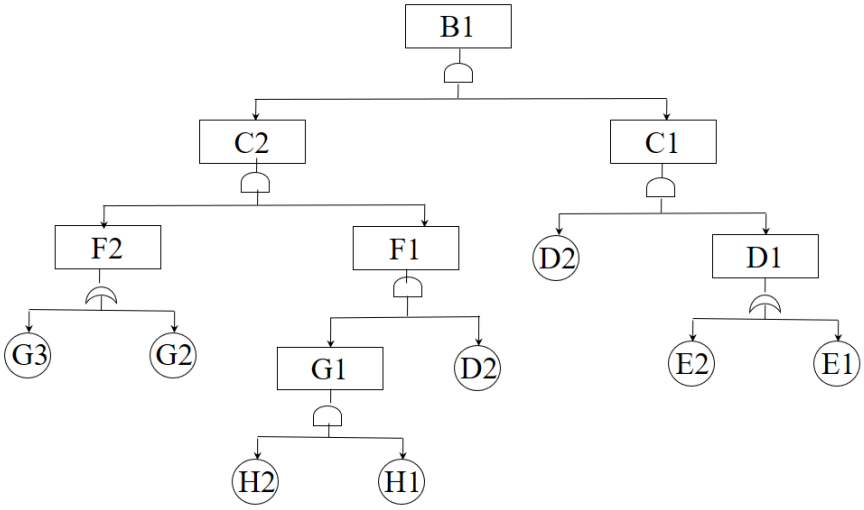

Figure 6. Fault tree of ship collisions with wind turbines.

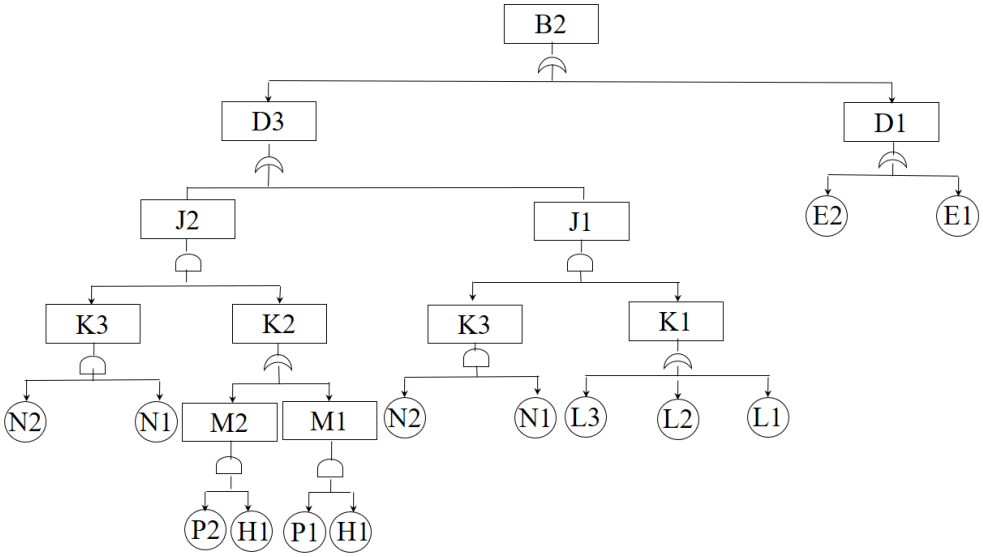

Figure 7. Fault tree of ship-to-ship collisions.

Taking Equations (1) and (2) into the events in Figure 6, the following Equation (3) is derived:

$$\begin{array}{rl} \text{B1} & = \text{C1} \,.\, \text{C2} \\ & = \text{D1} \,.\, \text{D2} \,.\, \text{F1} \,.\, \text{F2} \\ = & (\text{E1} + \text{E2}) \,.\, \text{D2} \,.\, \text{D2} \,.\, \text{G1} \,.\, (\text{G2} + \text{G3}) \\ = & (\text{E1} + \text{E2}) \,.\, \text{D2} \,.\, \text{D2} \,.\, \text{H1} \,.\, \text{H2} \,.\, (\text{G2} + \text{G3}) \end{array} \quad (3)$$

According to the law of identity (i.e., D2 . D2 = D2) [29], Equation (3) can be rewritten as Equation (4):

$$(\text{E1} + \text{E2}) \,.\, \text{D2} \,.\, \text{H1} \,.\, \text{H2} \,.\, (\text{G2} + \text{G3}) = \text{H1} \,.\, \text{H2} \,.\, \text{D2} \,.\, [(\text{E1} \,.\, \text{G2}) + (\text{E2} \,.\, \text{G2}) + (\text{E1} \,.\, \text{G3}) + (\text{E2} \,.\, \text{G3})] \quad (4)$$

With reference to the events in Table 1, the intersection of (H1 . H2) represents the fact that the offshore wind farms and the navigation channels exist. Therefore, Equation (4) can be simplified to Equation (5), which implies the basic events (minimal cut-off) of the ship colliding with the wind turbine.

$$(\text{D2} \,.\, \text{E1} \,.\, \text{G2}) + (\text{D2} \,.\, \text{E2} \,.\, \text{G2}) + (\text{D2} \,.\, \text{E1} \,.\, \text{G3}) + (\text{D2} \,.\, \text{E2} \,.\, \text{G3}) \quad (5)$$

Bringing Equations (1) and (2) of Boolean algebra into the events in Figure 7, Equation (6) can be derived as follows:

$$\begin{aligned} B2 &= D1 + D3 \\ &= (E1 + E2) + (J1 + J2) \\ &= (E1 + E2) + (K1 \,.\, K3 + K2 \,.\, K3) \\ &= (E1 + E2) + [(L1 + L2 + L3) \,.\, (N1 \,.\, N2) + (M1 + M2) \,.\, (N1 \,.\, N2)] \\ &= (E1 + E2) + [(L1 + L2 + L3) \,.\, (N1 \,.\, N2) + (H1 \,.\, P1 + H1 \,.\, P2) \,.\, (N1 \,.\, N2)] \\ &= (E1 + E2) + (N1 \,.\, N2)\,[(L1 + L2 + L3) + (H1 \,.\, P1 + H1 \,.\, P2)] \\ &= (E1 + E2) + (N1 \,.\, N2 \,.\, L1) + (N1 \,.\, N2 \,.\, L2) + (N1 \,.\, N2 \,.\, L3) + (N1 \,.\, N2 \,.\, H1 \,.\, P1) + (N1 \,.\, N2 \,.\, H1 \,.\, P2) \end{aligned} \quad (6)$$

4. Influencing Factors for Navigation Safety within Offshore Wind Farms

The possible factors leading to maritime incidents are environmental factors, human errors, and mechanical failures [33]. Environmental factors can be further classified into naturally environmental and artificially environmental factors. In particular, wind, waves, and visibility are the main naturally environmental factors [34], while the artificially environmental factors refer to offshore wind farms. Those artificially environmental factors have complex effects on navigation safety if combined with human errors or marine machinery failures. The number of accidents in offshore wind energy farms has increased significantly in recent years. In Europe, for example, there were 164 accidents on average per year from 2012 to 2016, of which vessel collision was one of the major accidents [35]. In addition, vessels may be forced to make a detour due to the obstruction of offshore wind farms, which increases the voyage course and navigation time [36].

According to Weng et al. [37], the factors affecting the vessel collision frequency are: (i) traffic flow, (ii) traffic density, (iii) channel width, (iv) adverse weather, and (v) environmental darkness. Environmental darkness is the greatest affecting factor. Theoretically, there are more factors affecting the vessel collision frequency. However, it is necessary to especially emphasize that the frequency of vessel collision, including collisions between vessels and between vessels and wind turbines, may be higher due to the construction of offshore wind farms. In particular, because of the large number of fishing vessels in the Taiwan Strait over the years, the risk extent of sailing in the fishing areas is high [38]. The reduction of fishing areas and navigable sea caused by construction of offshore wind farms increases both the traffic density in navigation channels and collision risks [36]. In addition, the operation pressure of larger-sized vessels has increased in limited channel spaces in recent years. Regarding the possible effects of offshore wind farms on navigation safety, the European Maritime Spatial Planning (MSP, European Commission, Brussels, Belgium) Platform in 2021 confirmed that the construction of offshore wind farms may negatively affect the safety and efficiency of marine transport. The Offshore Renewable Energy Installations Safety Response Guidance (MGN 543) issued by the Maritime and Coastguard Agency (London, UK) [39] further suggests that all reasonably foreseeable obstacles or risks to navigation or marine emergency disposal shall be assessed prior to building any offshore wind farm. The possible factors for navigation safety within offshore wind farms are assessed in this study and discussed in the following sections.

4.1. Great Reduction of Navigation Space

The size, quantity, and space occupation of offshore wind turbines directly reduce the navigation space of vessels. The rotor diameter of current mainstream wind turbines is 110–130 m [40]. In order to improve the efficiency and service life of wind turbines, the theoretical distance between wind turbines shall not be less than four times the rotor diameter [41]. At present, in most offshore wind farms, the distance used is 6–10 times the rotor diameter. For large wind farms with hundreds of wind turbines, the appropriate distance between wind turbines is recommended to be 15 times the rotor diameter [42]. Taiwan intends to build a total offshore wind power capacity of 15.6 GW by 2035. Based on the current mainstream 8-MW wind turbines, about 1950 wind turbines shall be built. While based on 15 times the rotor diameter, each wind turbine occupies 2.72–3.8 m^2, and

1950 wind turbines require 5304–7410 m^2. Hence, its reduction of existing navigation space cannot be ignored. According to Figure 1, the feasible powers of the wind energy farm can be developed in 5–20 m deep of shallow sea, and in 20–50-m-deep sea are 1.2 GW and 10 GW, respectively [11]. Therefore, at least 4.4 GW shall be developed in the sea with an ocean depth of more than 50 m in the future to achieve the capacity goal of 15.6 GW by 2035.

4.1.1. Raising the Vessel Density Distribution in Navigation Channels within Offshore Wind Farms

The vessel density distribution is an important factor in assessing the complex marine traffic flow and collision risks [43]. The vessel density in the sea represents the navigation indicator, which is related to port construction and the national economic development [44]. In recent years, traffic complexity has become a prevalent topic in marine traffic management [43]. There are a large number of direct cross-strait vessels sailing between Taiwan and the Chinese Mainland. In 2020 alone, 22,980 vessels entered and left Taiwan's ports [45]. In consequence, these direct vessels between Taiwan and the Chinese Mainland increase the vessel density distribution in the sea.

A large number of fishing vessels is one of the reasons for such a high vessel density of the western sea in Taiwan. However, fishing vessels in the sea are not only for sailing but also for fishing in specific fishing regions, which makes the vessel density distribution in the sea more complex. The sea around Taiwan is rich in fishery resources, attracting an enormous number of fishing vessels [46]. These fishing vessels may be from various fishing ports in Taiwan or from other countries [47]. After offshore wind farms are gradually built and completed, the sailing routes of merchant and fishing vessels will be changed and significantly raise the vessel density distribution.

Marine incidents generally cost very much and may lead to heavy casualties or serious environmental damages [36]. Considering that management policy is one of the factors affecting vessel accidents [48], the complex relationship between vessel accident risks and navigation safety policy is significant [33]. The complex sailing patterns and high vessel density distribution, which are deeply affected by offshore wind farm development, have become normal in the western sea of Taiwan.

4.1.2. Increasing Vessel Traffic Flow in Navigation Channels within Offshore Wind Farms

A large vessel traffic flow is a severe challenge to navigation safety [38] and one of the significant factors leading to maritime incidents [49]. The vessel collision accident rate is frequently proportional to the square of the vessel traffic density. The vessel traffic density reflects the business and risk levels of vessel traffic flow in specific seas to some extent [50]. The vessel traffic density is inversely proportional to the available area of navigable sea. Commercial, industrial, and fishing ports are densely distributed along Taiwan's western coast from north to south. Figure 8 [30] shows the heavy vessel traffic flow in the western sea of Taiwan. In the future, after the wind farms are all built in the open sea outside the middle of Taiwan, except fishing vessels or some shallow draft vessels that may sail in the inshore traffic zone to the east of the wind farm, most vessels sailing to Northern or Southern Taiwan will be gathered in the navigation channels of the wind farm, leading to high vessel density in the navigation channels. The navigation space between the outer limits of the territorial sea and the west coast from the middle of Taiwan in the northbound direction will significantly narrow down (Figure 9).

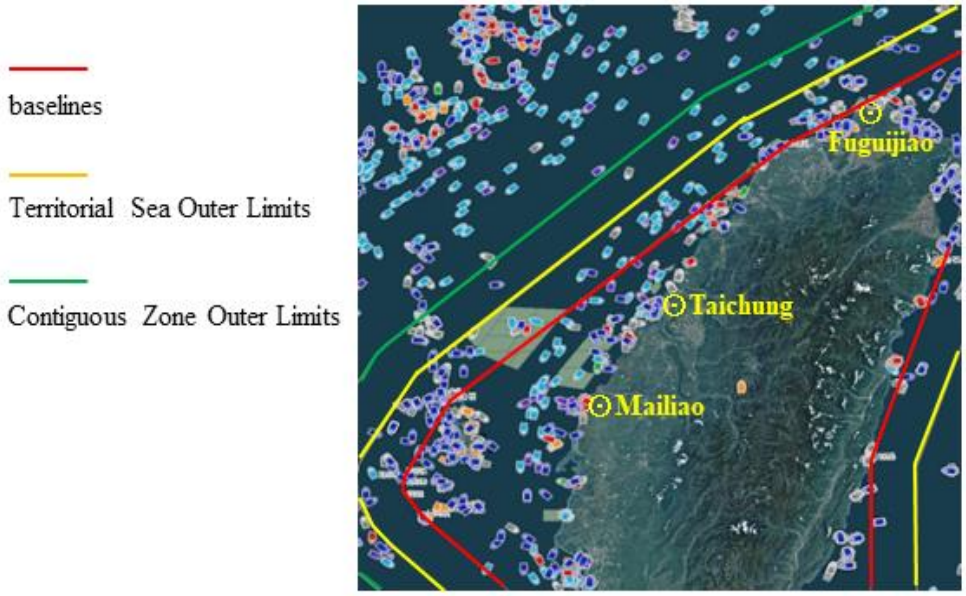

Figure 8. Crowded ship flows in the Taiwan Strait close to the Taiwan western coast. Source: plotted by the authors based on the information in Reference [30].

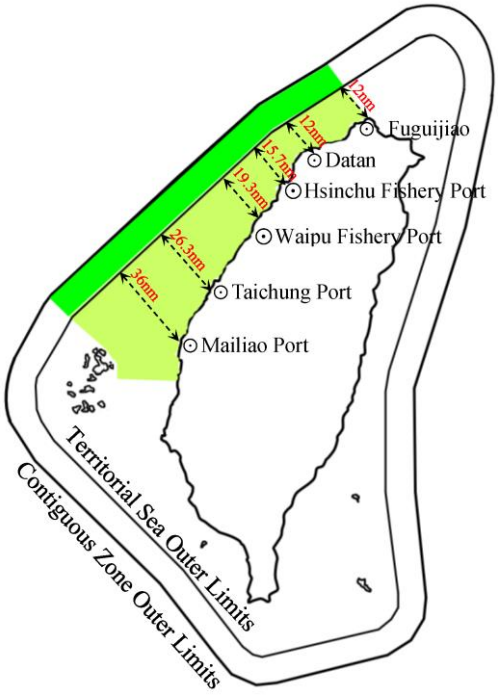

Figure 9. Width variations of the navigation channel within the offshore wind farm off of Taiwan's western coast. Source: plotted by the authors.

4.1.3. Large Space Reduction for Vessel Avoidance

Each vessel has its own operational characteristics, and the turning circle of each vessel represents the most basic steering performance. The diameter of turning circle is also an important indicator of vessel maneuverability [51]. While vessel avoidance is inevitable during navigation, heading change is one of the main methods to avoid colliding with other vessels. Hence, the navigable space must contain the sea width required for vessel avoidance. The MSC.137 (76) resolution on the "Standards for Ship Maneuverability" enforced by the IMO effective from 2002 specifies that the tactical diameter of a vessel's steering performance shall not exceed five times its vessel length [52].

A large number of offshore wind turbines inevitably occupy navigable ocean space. In addition, just a few or even a single wind turbine can divide the whole sea, which results in blocking up the navigable space and reducing the ocean space needed for vessel avoidance. In particular, to change a heading for avoidance, the ocean space needed in crossing situations is larger than in head-on and overtaking situations. For example, there are many wind turbines on the east and west sides of the offshore wind farms in the open sea outside the middle of Taiwan, so that vessels sailing in the navigation channels of the wind farms can only complete all navigation actions and processes, including vessel avoidance, in the navigation channels. On the other hand, as the diameter of a vessel's turning circle is proportional to its vessel speed and length [53], which are two of the determining factors for maritime incidents [54]. In other words, in offshore wind farms, there are more restrictions on the navigable space for large-sized vessels and high-speed vessels than for small-sized vessels and low-speed vessels. This implies that the reduction of navigable space for vessels by offshore wind farms would increase the probability of maritime accident risk.

4.2. Shadowing Effects on Navigation Channels

According to the provisions on the look-out in the International Regulations for Preventing Collisions at Sea [55], vessels shall always maintain a proper look-out by sight and hearing, as well as by all available means appropriate in the prevailing circumstances and conditions, to fully understand the situations and collision risks. This provision indicates that any circumstance that shadows or interferes with the navigators on duty to look out by sight, hearing, or any other means is a threat to navigation safety. Lighthouses and port light poles distributed along Taiwan's western coast may be shadowed by offshore wind turbines. This may not only affect navigation safety but also disorientate most small fishing vessels or rafts that can only visually identify lighthouses and light poles. Another shadowing phenomenon is that, in many cases, offshore wind farms or even a single wind turbine can seriously affect the signal reception of marine electronic aids to navigation [56].

In addition to look-outs by sight and hearing, radar has been used in merchant vessels since the 1950s and has become a look-out tool commonly used by navigators. According to offshore wind farm experiences in Europe, offshore wind turbines may interfere with navigation equipment such as radar to varying degrees [57], which block radar beams, thus producing shadowing effects [58]. Wind turbines also produce interference signals, affecting radar systems' performances [59]. Wind turbine blades rotate to produce Doppler ambiguities [59] so that navigators make mistakes in judging the distance and speed of observed targets. Moreover, the vessel traffic services (VTS) of ports in Taiwan and of navigation channels in the offshore wind farms on the western coast outside the middle of Taiwan monitor vessels by radar and AIS, which are very likely to be blocked or interfered by offshore wind turbines, thus affecting the navigation safety management.

4.3. Increase of Collision Risks by Fishing Vessels Crossing Navigation Channels

In the absence of offshore wind farms, fishing vessels and rafts from fishing ports along Taiwan's western coast sail in a straight line to the fishing areas. On the other hand, merchant vessels sailing in the north–southbound direction can generally anticipate their attempts from enough distance through effective look-outs. In contrast, after wind farms are built, wind turbines are placed adjacent to each other. If fishing vessels are not forbidden to enter wind farms and merchant vessels sail in navigation channels, wind turbines placed adjacent to each other are like blocking gates, where fishing vessels may jump out at any time. Due to the obstruction of wind turbines, it is difficult to prevent fishing vessels from sailing diagonally from wind farms into or across navigation channels.

The vessel collision frequency in specific seas is equal to the number of encounters times the causation probability [60]. Offshore wind farms composed of many wind turbines reduce, obstruct, and shadow the navigation space, which is likely to increase the probability of vessel collision.

4.4. Increasing the Colliding Probability of Breakdown Vessels with Wind Turbines

The buffer distance between vessels and wind turbines is relatively curtailed due to the great reduction of navigable space by offshore wind farms. Therefore, in the case of power loss due to engine breakdown during navigation, the speed over ground is created under the influence of wind, flow, and wave [61], which will lead to the risk of vessel collision with wind turbines. Part of the Kuroshio Current Branch that flows westward crosses the Bashi Channel and then merges with the warm current of South China Sea to form the Taiwan Strait current, which then flows northward [62]. The southwest monsoon is not as strong as the northeast monsoon, but if combined with the Taiwan Strait current, the effects on vessels cannot be ignored.

Machine breakdown is not the only reason for losing power; fire, explosions, collisions, and even extremely bad sea conditions may also cause failures in vessel control and, finally, lead to serious disasters. A total of 109 maritime incidents [63] (Table 2) occurred in the same sea region as the main development sea region of offshore wind farms outside Western Taiwan in the past 7 years (2014–2020), with a similar occurring frequency each year. In the future, after the sea is full of wind turbines, in the case of similar maritime incidents, wind turbines may become the first victims. During typhoons, strong northeasterly winds, or bad sea conditions, wind turbines may be hit, because large containers or cargos carried by vessels fall into the sea and float on the surface. The fallen cargos and mechanical parts from the hit wind turbines will obstruct the navigation channels of the wind farms, which cause negative chain effects on the navigation safety.

Table 2. Previous maritime accidents that occurred in the same area of the main planned offshore wind farms.

Year	Collision	Aground	Fire	Machine Failure	Twisted Net	Total
2014	3	2	4	4	4	17
2015	5	3	3	5	0	16
2016	2	3	1	2	6	14
2017	5	2	2	7	1	17
2018	4	5	0	5	0	14
2019	5	2	3	5	0	15
2020	4	1	2	7	2	16

5. Developing Promising Strategies to Improve Navigation Safety in Wind Farms

According to the above analysis of the navigation problems, this study developed three effective strategies to improve the navigation safety in offshore wind farms so as to balance both the development of offshore wind power and the navigation safety in offshore wind farms.

5.1. Comprehensive Marine Spatial Planning for Offshore Wind Farms

Although both shipping and fishery activities can highly coexist in the wide sea, they are almost excluded in the ocean space of the offshore wind farms. Offshore wind power is important to the economic development and livelihood of the people in Taiwan. However, shipping and fishery activities are vital to foreign trade development and seafood acquisition and are also important industries in Taiwan. Therefore, evenly and effectively using the ocean is the basic cognition for Taiwan to develop its offshore wind farms. Effective marine spatial planning can predict various marine uses so as to allocate the required space [64,65].

According to Figure 8, most vessels in the western sea of Taiwan usually sail in the territorial sea and internal sea. There are three main reasons that raise the navigation efficiency for avoiding sailing too far from shores, increasing the voyage range, and making use of the terrain of Taiwan particularly during the northeast monsoon to reduce the wind strength and improve the navigation safety. However, the planning and constructing offshore wind farms obviously have a competition–cooperation relationship with the

available navigable space. In accordance with the United Nations Convention on the Law of the Sea in 1982, coastal states have the sovereign right to engage in economic development and exploration within their exclusive economic zones, such as the utilization of seawater, currents, and wind power [66]. For example, in Germany, most offshore wind farms are built within their exclusive economic zone in the North Sea [29] about 115 km away from the shore.

The navigable space within the territorial sea is likely to be excessively compressed by wind farms. In particular, according to Figure 9, the area within the territorial sea in northern Taiwan is not half as wide as that outside the middle of Taiwan. Building offshore wind farms pushes the navigable space away to the open sea, which not only increases the sailing distance between the ports along Taiwan's western coast but also makes navigation more difficult. The navigation risks increase as well, especially during the northeast monsoon due to no shadowing protection from the terrain of Taiwan. Moreover, in accordance with the United Nations Convention on the Law of the Sea in 1982, although coastal states only have management authority over vessel navigation in territorial seas and internal seas [66], it is difficult to achieve effective navigation management if vessels are pushed across the outer limits of the territorial sea and move far away from the west coast of Taiwan.

In recent years, the global development of mega-large container vessels has accelerated [65]. Ninety-one mega-large container vessels with carrying capacities of 18,000–23,000 TEU were put into operation from 2015 to 2019 [67]. Each vessel had a carrying capacity of 24,000 TEU and a length of 400 m [68] in 2020. The vessel length will be expected to reach 453 m when the carrying capacity is 30,000 TEU [69]. As the vessel length increases, the space required for vessels to operate will increase. According to IMO MSC.137 (76), for any vessel with the minimum maneuvering capability, the tactical diameter shall not be greater than five times the vessel length. This implies that the channel width shall not be less than 8.64 nautical miles. Moreover, the channel width shall not be less than 9.78 nautical miles if the carrying capacity of a future container vessel is expected to reach 30,000 TEU with a vessel length of 453 m. Hence, within offshore wind farms in the sea north of the middle of Taiwan, the navigation channel shall be at least 9 nautical miles wide.

The sea area within the territorial sea north of Central Taiwan gradually narrows northward (Figure 9). After 9 nautical miles of channel width is deducted, the area available for offshore wind farm development is reduced. The only solution is to move the area of sea for offshore wind farm development to adjacent areas (part of the economic zone). Therefore, in pursuing navigation safety and developing the offshore wind farm, the planning shall be comprehensively developed with the whole sea taken into consideration. Additionally, the limitation of building offshore wind farms only within the territorial sea area shall be removed.

5.2. Integrating Vessel Traffic System and Providing Remote Pilotage Services

The negative effects of offshore wind farms on navigation safety can be significantly mitigated by the vessel traffic system (VTS) in the whole western sea of Taiwan. The first task is to integrate the VTS of the navigation channel in offshore wind farms and the existing VTS in the ports adjacent to the offshore wind farms along Taiwan's western coast. The integrating VTS can effectively convey a vessel monitoring message to avoid various navigation warnings by the same vessel issued from different VTSs while vessels enter and leave the regions of the offshore wind farms.

As the wind farms are located on both sides of the navigation channel, various working vessels to maintain wind farms frequently cross the navigation channel, causing great interference to other vessels in the channel. However, the built wind farms have reef effects on the marine environment [70], significantly enhancing the diversity of the marine species and increasing the total number of fish [70], especially in the recreational fishery areas [71]. If entering offshore wind farms is not restricted, fishing vessels will cross the navigation channels within wind farms frequently. Even though these working vessels and

fishing vessels report to the VTS of offshore wind farms while crossing navigation channels, only the VTS can alert other vessels in navigation channels. However, the VTS cannot warn the merchant vessels that fishing vessels are crossing the navigation channels within wind farms. It is suggested that two to three open sea areas between wind turbines could be specified for fishing vessels to sail across the wind turbines in order to reduce the collision risks effectively. Since the distances between adjacent wind farms can be used for isolation, they could be used as the most appropriate navigation channel for fishing vessels.

Changing a navigation heading cannot effectively avoid vessel collisions. Instead, the collision risk can be reduced by decelerating vessel sailing [72]. In particular, the vessels are required to flexibly adjust their speed at any time to avoid any fishing vessel that may jump out and cross navigation channels. However, no matter which collision avoidance measure is taken, such as course change or deceleration, the distance between two vessels is the key factor for collision avoidance. Thus, it is necessary to maintain a safe distance between vessels, known as the ship domain [73]. As the relative movement of vessels in the navigation channels is mainly overtaken, the collision possibility can be greatly reduced by maintaining a certain ship domain. If vessels are in the precautionary areas shown in Figure 3, they leave the navigation channels and are no longer monitored by the VTS of offshore wind farms. In such areas, there are vessels entering and leaving the ports and navigation channels that have a higher traffic density and complex vessel flow [27]. Hence, vessels sailing in the precautionary areas are required to adopt the stand-by engine measure to help deceleration at any time and strengthen the collision avoidance. Large-sized merchant vessels or fully loaded ships navigating in the navigation channel have relatively higher risks. Remote pilotage services that can reduce such navigation risks are thus suggested to be provided by the authorities of wind farms in order for them to function effectively. As a consequence, on the basis of the overall vessel traffic system, appropriate vessel management measures shall be developed according to the navigation patterns of individual sea areas.

A practical way to reduce the existing shadowing effects of wind turbines is to provide additional marine aids to navigation at appropriate wind turbines or at nearby facilities. As defined by the International Association of Lighthouse Authorities (IALA, Saint-Germain-en-Laye, France) [74], marine aids to navigation refer to peripheral equipment, systems, or services artificially designed for vessels to enhance maritime traffic safety, improve navigation efficiency, and protect the marine environment, such as lighthouses, buoys, channel systems, and VTS. Considering the traffic volume and risk level, various marine aids to navigation are often the primary measure for maritime traffic management. However, if the marine aids to navigation for the whole sea are not consistent, not only will the benefits be lost, but the navigators will also be confused and make poor judgments. According to Chapter 5 of SOLAS, in building marine aids to navigation, the international recommendations and guidelines shall be taken into account to obtain the greatest possible uniformity. The current warnings and marks of navigation channels within offshore wind farms or requirements for installing marine aids to navigation are mainly based on the IALA recommendation O-139 [75] to meet the principles of SOLAS.

In addition, when a ship enters and exits the navigation channel, the wind turbines on both sides of the channel may confuse the navigator of the ship to mistakenly identify the channel entrance, resulting in wrongly entering the offshore wind farms. To reduce such errors, the wind turbine rotors on both sides of the entrance of the navigation channel should be in a more recognizable color such as red, which wavelength is the longest, so that the navigator of the vessel can judge the channel entrance immediately. Consequently, all wind farms shall have overall planning to avoid the confusion for crew members in using the aids.

5.3. Building and Docking of Salvage Vessels

Due to the heavy marine traffic around Taiwan and the harsh meteorological conditions in this ocean region, there are many maritime incidents every year [76]. Table 2

shows the annual number of maritime accidents in the area of offshore wind farms of the western coast of Taiwan. As offshore wind farms are built one after another, there may be more maritime accidents and collisions between vessels and wind turbines in the future. Therefore, coping measures, equipment, and response mechanisms shall be prepared. This study suggests that the marine salvage vessels shall be built to prevent collision between vessels and wind turbines. The reasons for requiring the salvage vessels are explained below.

According to the vessel requirements for offshore wind farms at different development stages, such as construction, operation, and decommissioning, the vessel characteristics needed are different. Noteworthy, there are collision risks between vessels and wind turbines at any time during at least 20 years of operation. Thus, preventive maintenance is necessary [77]. The VTS monitors vessel navigation by AIS or radar, which is one of the preventive maintenance measures. If necessary, VHF can be used to remind or warn sailing vessels to prevent vessels from colliding with wind turbines. When vessels lose their power, there is no alternative but to provide immediate towing assistance. In order to effectively tow wrecked vessels away from the offshore wind farms immediately, the sailing speed and engine performance of salvage vessels, the distance between ports and incident sites, and the abilities of salvage vessels to withstand the adverse sea conditions, particularly during the northeast monsoon in the Taiwan Strait, shall be considered. Hence, the management authority of the offshore wind farm shall build and operate salvage vessels for special emergencies to resolve collisions between vessels or between vessels and wind turbines.

Those salvage vessels with strong towing performances shall anchor in ports near offshore wind farms to carry out the practical and effective rescue role. The expenses incurred shall be borne by the owner of the accidental vessel. When offshore wind turbines are collided by vessels, the navigation channels may thereafter be blocked to affect marine traffic flow. The marine environment may be polluted as well. Therefore, preventive and protective measures such as anchoring salvage vessels in nearby ports shall be taken into account when developing offshore wind farms.

5.4. Result Validation of the Fault Tree Analysis

In Equation (5), (D2 . E1 . G2), (D2 . E2 . G2), (D2 . E1 . G3), and (D2 . E2 . G3) are the four intersections that are the minimum cut-off sets of B1. Referring again to the events in Table 1, Equation (5) can be explained as follows:

(1) When the ship's machinery fails and the salvage ship is far away, the ship may collide with the wind turbine due to current drifting.
(2) When the ship's propeller is twisted and the salvage ship is far away, the ship may collide with the wind turbine due to drifting in the ocean.
(3) When the ship's propeller is twisted and no salvage ship is available, the ship may collide with the wind turbine due to current drifting.

Based on the above four points, the ship out of control is a main cause of the ship collision with the wind turbine. In order to prevent that accident, it is necessary to build a suitable salvage ship and standby nearby.

In Equation (6), (E1 + E2) is a union, and (N1 . N2 . L1), (N1 . N2 . L2), (N1 . N2 . L3), (N1 . N2 . H1 . P1), and (N1 . N2 . H1 . P2) are the five intersections that are the minimum cut-off sets of B2. Referring again to the events in Table 1, Equation (6) can be explained as follows:

(1) When the ship's machinery fails or the propeller is twisted, the ship may collide with the ship.
(2) The shadowing effects of wind turbines, coupled with the unfit function of VTS and the lack of navigation aids, may cause ships to collide with ships.
(3) Fishery ships frequently cross the navigation channel, and coupled with the unfit function of VTS and the lack of navigation aids, may cause ships to collide with ships.

(4) Fishery ships cross the navigation channel between the turbines, and coupled with the unfit function of VTS and the lack of navigation aids, may cause ships to collide with ships.
(5) The channel where there is a large flow of ships, coupled with the unfit function of VTS and the lack of navigation aids, may cause ships to collide with ships.
(6) High ship density distribution in the channel, coupled with the unfit function of VTS and the lack of navigation aids, may cause ships to collide with ships.

Based on the above six points, a ship out of control, high ship traffic flow, high ship density distribution, unfit functions of VTS and navigation aids, and frequently and arbitrarily crossing the navigation channel of fishery ships in the space between wind turbines are the main causes of ships colliding with ships in the navigation channel of offshore wind farms. In order to prevent that accident, it is extremely important to provide assistance to ships, especially VTS and navigation aids.

5.5. Discussion

Offshore wind farms in the western sea of the Taiwan Strait are built roughly in the north–southbound direction of Taiwan so that the navigation channels in offshore wind farms are in the same direction. The navigation channels within offshore wind farms north of the middle of the Taiwan Strait are separated into northbound and southbound lanes. Dense wind farms are established on both sides with limited navigable space, high traffic flow density, and a narrow distance between vessels. Hence, offshore wind farms indeed affect the navigation safety in wind farms. Based on the analysis in this study, the measures for promoting navigation safety are proposed and discussed.

Due to potential factors such as wind energy, water depth, and regulations, the sea to the east side of the outer limits of the territorial sea from the north of the middle of Taiwan to Fuguijiao, where offshore wind farms are concentrated, are overlapped with the sea for conventional navigation and fishing. The overlapping sea reduces the navigable space and seriously affects the long-established navigation patterns and raises the vessel density distribution. The free sailing of fishing vessels within offshore wind farms may lead to accidentally crossing navigation channels, increasing the sailing risks of other vessels in navigation channels within the wind farms. Hence, adequate measures to restrict the sailing routes of fishing vessels within offshore wind farms might be considered. A comprehensive and effective navigation management system shall be well-developed for the overall offshore wind farms. Remote pilotage services are suggested to be provided by the authorities of the wind farms. Finally, preventive measures and emergency strategies shall be adopted to prevent the increase of the navigation risks from building offshore wind farms.

5.6. Policy Implication

Due to the constraints of various coastal water environments, different developers might choose construction sites in the same water regions to develop adjacent offshore wind farms. Moreover, it extends from the coastal shallow water area to the deep water region, which occupies most of the navigation areas regularly used by merchants or fishing vessels. Vessels heading to ports in Western Taiwan mostly sail in the territorial sea and internal sea, exactly the same sea as the offshore wind farms are set. Therefore, the wind farms to be built in the future will reduce the navigation space, as analyzed in this study.

Taiwan's offshore wind farm policy is not only to obtain alternative wind energy but also to gain expertise from offshore wind farm development. In addition, wind energy development policies shall cope with the overall marine spatial planning and coordinate with the overall navigation safety planning. Three promising strategies for promoting navigation safety within the offshore wind farms were thus proposed and evaluated, which are comprehensive marine spatial planning for offshore wind farms, integrating vessel traffic system and providing remote pilotage services, and the building and docking of salvage vessels. The purposes of the proposed strategies are to assure the simultaneously

successful development of offshore wind farms and the promotion of the navigation safety of various vessels sailing within the farm region. Figure 10 reveals the framework of the strategy development in this study.

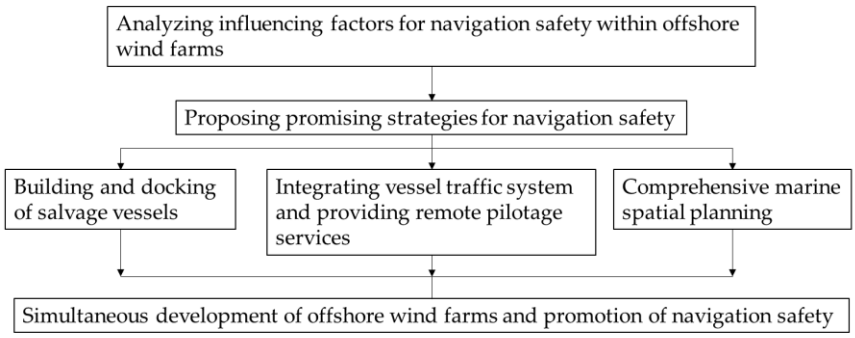

Figure 10. Framework of the proposed strategies for promoting navigation safety.

6. Conclusions

The navigation safety in offshore wind farms is related to the successful development of offshore wind farms. When the region of traditional navigation channel is built with infrastructure of offshore wind turbines, marine vessels can only sail in a navigation channel surrounded with plenty of wind turbines on both sides. The establishment of offshore wind farms has negative effects on navigation safety based on the present analysis. The offshore wind farms will cause a reduction of the navigation space and increase the vessel flow and density distribution in the channel, leading to increasing collision risks between vessels. Especially when a ship is out of control, the possibility of its colliding with a wind turbine is rather high. Fishing vessels frequently and arbitrarily cross the navigation channel containing the offshore wind farms, which will also increase the extent of collision risks with other ships. Effective strategies for improving the navigation safety in the limited sea area of the offshore wind farms were proposed and evaluated in this study. A comprehensive plan for using the whole ocean space to simultaneously pursue the efficient operation of offshore wind farms and enhancement of navigation safety was suggested. In addition, an integrating vessel traffic system of the offshore wind farms and neighboring commercial and industrial ports along the coast of the Taiwan Strait could be established. A remote pilotage service system was suggested to be provided by the authorities of the offshore wind farms in order to function effectively. The systems and marks of marine aids to navigation built at different periods in the whole sea of the offshore wind farms should be consistent. Moreover, salvage vessels shall be built for marine accidents and permanently anchored in nearby ports to effectively reduce the risk of collisions within sea region of the offshore wind farms.

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