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A System-Theory and Complex Network-Fused Approach to Analyze Vessel–Wind Turbine Allisions in Offshore Wind Farm Waters

Kai Yan [1,2,3,4], Yanhui Wang [1,2,*], Wenhao Wang [1,2], Chunfu Qiao [3,4], Bing Chen [3,4] and Limin Jia [1,2,4]

1 State Key Laboratory of Advanced Rail Autonomous Operation, Beijing Jiaotong University, Beijing 100044, China
2 School of Traffic and Transportation, Beijing Jiaotong University, Beijing 100044, China
3 Transport Planning and Research Institute, Ministry of Transport, Beijing 100028, China
4 Laboratory of Transport Safety and Emergency Technology, Beijing 100028, China
* Correspondence: wangyanhui@bjtu.edu.cn; Tel.: +86-18910186600

Abstract: Given the national goal of "emission peaking and carbon neutralization", China has become the largest country in the world for offshore wind farm construction. At the same time, navigational safety problems in offshore wind farm waters have become increasingly frequent. Owing to the complexity of offshore wind farm waters and the small number of accident data samples available for reference, the system theory method is more suitable for selection than the traditional method. Based on causal analysis based on system theory (CAST) and a complex network (CN), in this study, a qualitative and quantitative accident analysis model, CAST-CN, is constructed to analyze a complete case of vessel and wind turbine allision in offshore wind farm waters. The results show that, at the micro level, in addition to the master, crew, shipping company, and typhoon Hato, the maritime safety administration and the wind farm operation management department have a certain impact on the development of the accident discussed in this study. At the macro level, internal and external factors leading to the lack of system safety are identified, and measures and suggestions for system safety improvement are proposed based on analysis. This study can fill the research gap in the systematic analysis of traffic accidents in offshore wind farm waters and provide support for the safety assessment and decision-making of government management departments and research institutes.

Keywords: accident analysis; offshore wind farm; STAMP; CAST; complex network

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1. Introduction

1.1. Background

With the global vision of carbon neutrality, offshore wind power is going through a phase of rapid growth worldwide. China has always considered the development of the wind power industry as an important means to achieve "emission peaking and carbon neutralization". Supported by the subsidy policy, China has surpassed the UK to become the world's largest country in terms of total installed offshore wind power capacity at a stunning rate. As shown in Figure 1, approximately 21.1 GW of new offshore wind power capacity was added globally in 2021, and the cumulative installed capacity reached 57 GW [1]. Meanwhile, 16.9 GW of offshore wind power was added in China, and the cumulative installed capacity is 27.7 GW, accounting for 80.1% and 48.4% of the total, respectively. With advantages such as large wind farm areas, low visual impact, high wind speed, and low transmission cost, offshore wind power has great potential for development, and the scale of installed offshore wind power is expected to continue to exceed expectations [2]. Due to the high development trend of offshore wind power, the conflict of sea resources between the construction and operation of offshore wind farms (OWFs) and other sea-related activities has gradually increased, affecting the safety of ship navigation [3].

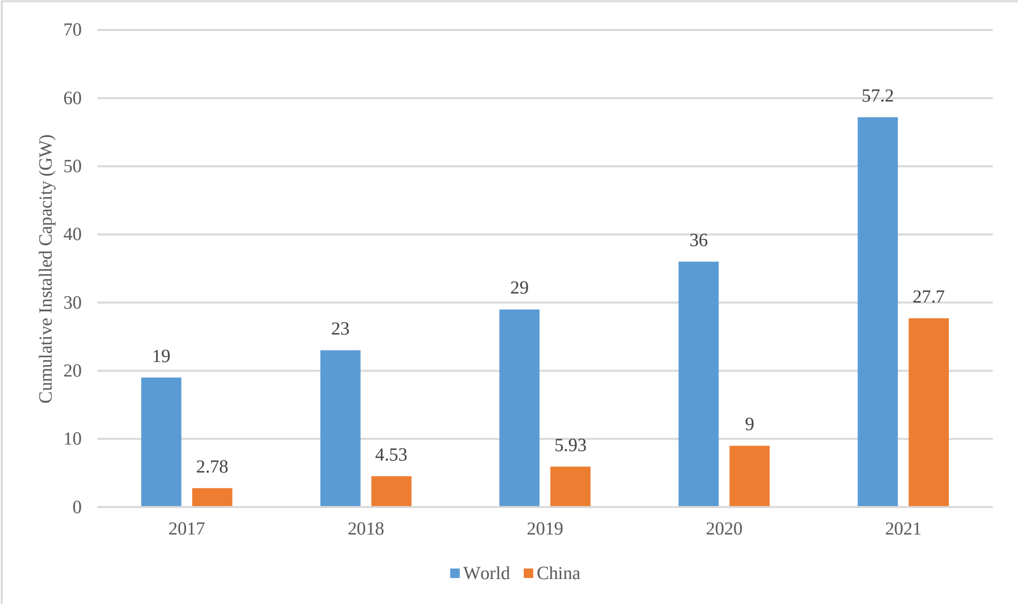

Figure 1. 2017–2021 Global and Chinese cumulative installed offshore wind power capacity.

Marine traffic is variously impacted by the construction of offshore wind farms. First, the presence of OWFs signifies that vessels must avoid more obstacles in the water and ensure no allisions between vessels and offshore wind facilities [4]. Second, OWFs may also limit the navigable space available to vessels, causing increased traffic density and an increased risk of collisions between vessels [5]. Additionally, the physical structure and electromagnetic characteristics of the wind turbine units of offshore wind turbines can interfere with—even block—shore-based perception and communication systems, such as the vessel traffic service system (VTS), the automatic identification system (AIS) and the very high frequency communication system (VHF), which may lead to the loss of the supervision and guidance for a vessel from the maritime safety administration (MSA), decreasing the navigational safety level [6,7], especially in extreme weather [3]. Moreover, due to the difficulty of the construction and operation, and maintenance of offshore wind farms, a large number of workers need to be transported by special engineering vessels (service vessels) to complete operations at sea, increasing safety risks.

Additionally, the combination of the above-mentioned influencing factors and strong wind energy significantly increases the risk of accidents in offshore wind farm waters, compared to other navigable waters [8]. The most common types of marine accidents in offshore wind farm waters are vessel–wind turbine allisions (VTAs), vessel–vessel collisions, and vessel sinking caused by wind disasters [9]. The analysis and prevention of VTAs are more complex and difficult than those of the latter two types of accidents, and this is because vessels have direct physical interactions with wind farm facilities. More companies and organizations are involved, especially during the construction phase of an offshore wind farm. Moreover, government safety supervision and legal policy formulation are categorized as two industry sectors. In China, for example, the safety management of vessels is handled by the China Maritime Safety Administration (China MSA) under the Ministry of Transport, while the site selection approval and safety supervision guidance of offshore wind farms is handled by the National Energy Administration under the Ministry of Natural Resources. Therefore, determining how to scientifically and effectively analyze and prevent VTA has become a focus of research on the navigational safety of offshore wind farms [10].

1.2. Related Works

The majority of accident analyses in offshore wind farm waters have been conducted based on the theory of accident causation, and the objective of these studies is to identify causal factors related to accidents, such as navigation environment, traffic flow conditions, machine failures, and human errors [3]. Scholars have analyzed various marine accidents arising from the construction and operation phases of offshore wind farms, as well as the corresponding risk influencing factors, to address the issue of navigational risk in offshore wind farm waters for vessels [11,12]. Commonly used methods include the Formal Safety Assessment (FSA) of the International Maritime Organization [13], fault tree [8,14,15], and Bayesian networks [16,17].

For example, Rawson and Brito used fault tree analysis to study the navigational risks associated with environmental changes caused by the construction of offshore wind farms, and their study showed that collisions were the most probable risks [18]. Dai established a system fault tree analysis of offshore wind farm operations, and the assessment showed that the key factors leading to accidents, such as offshore wind collapse, personal injury, ship collision, and damage to submarine cables, also included high winds, untimely maintenance, and collision avoidance failure [19]. Mehdi studied the dynamic risk assessment of vessels operating in the waters of offshore wind farms. The study showed that offshore wind farm facilities were detrimental to the navigational safety of passing vessels, the safe operation of wind farm support vessels, and emergency operations such as search and rescue (SAR), and that the risks of these operations resulted from the reduction of ocean space and the increase in traffic density [20]. To assess the overall navigational risk in offshore wind farm waters objectively and accurately, Mehdi selected several indicators from both natural conditions and the navigational environment, and constructed a model to assess the navigational risk of vessels in offshore wind farm waters, not considering factors such as personnel reliability, technical failures, and traffic management [21].

The traditional accident analysis methods mentioned above are widely employed in research in the field of ship navigation safety [22]. However, the issue of VTAs analysis in offshore wind farm waters requires simultaneous consideration of offshore wind farms, various types of vessels in the water, and other elements. This is a complex systemic problem, and the traditional risk assessment methods are unable to systematically analyze the connections between various elements [23]. Another key challenge in marine accident analysis in offshore wind farm waters concerns the scarcity of historical data on relevant accidents. Hence, qualitative methods such as expert judgment are more commonly used [24]. Qing Yu discussed the possibility of merchant vessel accidents due to offshore wind energy development off the Atlantic coast of the United States, enlisting the advice of nautical experts to assess the probability of allisions, collisions, or groundings of merchant vessels due to the presence of offshore wind farms [25,26]. In addition, owing to China's late start of offshore wind power, research literature and historical accident data are scarcer in China than in countries such as the UK [13,27]. Therefore, some machine learning methods that rely on large-scale data sets for Natural Language Processing(NLP) model training are difficult to apply to the analysis of VTA [28].

1.3. Objective and Outline

Against the background described above, the present study aims to construct a qualitative and quantitative accident analysis method based on system theory to analyze a complex VTA accident case [29]. The study comprehensively analyzes the development, cause, and impact degree of VTA accidents, and explores deeper influencing factors, thus providing new ideas for improving the intrinsic safety of ship navigation systems in offshore wind farm waters.

To this end, this paper introduces the causal analysis based on system theory (CAST) model, which is based on the Systems-Theoretic Accident Model and Process (STAMP), proposed by Professor Leveson of NASA Institute in 2004 [30], and creatively integrates complex network (CN) analysis methods [31]. A typical VTA accident occurring along the coast of China is selected as a case study [32]. Using the accident investigation report, the events chain is clarified, the accident causes are identified, the safety control structure model and complex network model are constructed, the importance of key nodes is evaluated, and the defects at the system level are analyzed from a macro perspective. Finally, suggestions for improvement are provided. In the second section, the framework of system analysis, methods used, and calculation indexes are introduced. The third section introduces the complete case analysis process. In the fourth section, the innovation, application significance, and limitations of research are discussed. Section 5 concludes the study and discusses future prospects.

2. Methodology

2.1. The Analysis Framework

The approach to analyzing VTA accidents in this study is based on the CAST model integrated complex network theory to achieve quantitative analysis results. As shown in Figure 2, the analysis framework is divided into three stages. Stage 1 is the initialization, and the accident narrative is completed by extracting valuable information from a VTA accident investigation report. Then the traffic system in offshore wind farm water (TSOWF) can be defined and the system hazard and the constraint can be identified as the fundamental step of the entire CAST analysis procedure. In Stage 2, microanalysis, a hierarchical safety control structure (HSCS) is designed first to depict and code both the system components and their relationships. The detailed analysis of all the system components is conducted based on the proximate events in the VTA accident and the coded HSCS. Then a V-T network/matrix is constructed and weighted according to the HSCS and the components analysis results. Finally, the network eigenvalues are computerized to attain the critical components in the TSOWF. In Stage 3, macroanalysis, the system deficiency in the VTA accident is identified and improvement recommendations are proposed.

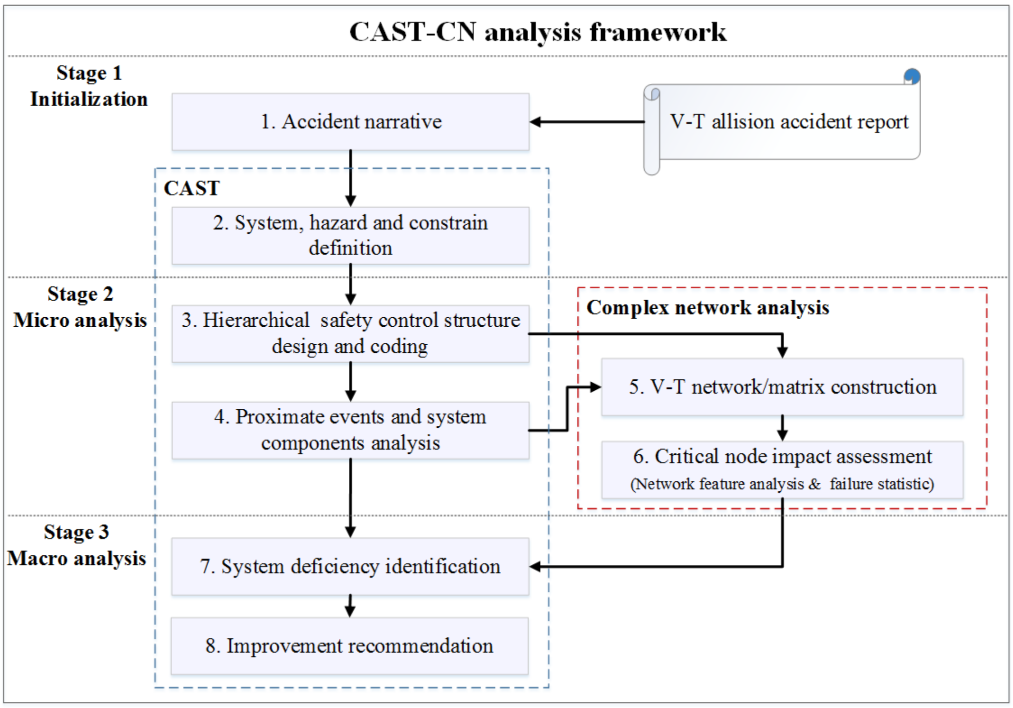

Figure 2. The analysis framework.

2.2. CAST Procedure

CAST is derived from STAMP, especially for accident qualitative analysis. Based on the idea underlying STAMP, CAST is created to fulfill the goals of analyzing all accident causes (optimized learning), reducing hindsight bias, systematically thinking about human behavior, providing blame-free explanations, and improving the safety control structure of the system [33]. The main analysis framework of CAST accords with STAMP, and comprises system and system hazard definitions, HSCS modeling, component analysis, control structure (system) flaw identification, and improvement suggestions. The difference lies in the fact that the system hazard identified by CAST is only related to the given accident scenario, and it is necessary to determine the proximate events leading to the loss [34]. Therefore, the procedure of CAST optimization and adjustment in this study is divided into five steps, as shown in Table 1.

Table 1. Experiment parameter setting.

Id	CAST Step	Details
1	Define system, hazard, constrain	(1) Define the system involved and the boundary of the analysis. (2) Describe the loss and identify the system's hazardous state (system hazard). (3) Identify the system safety requirements and constraints.
2	Design and code the hierarchical safety control structure (HSCS)	(1) Model the HSCS by learning from the existing system structure and the accident report. (2) Code the components (A–Z) and their relationships, including controls (C), feedback (F), communication (N), and physical impacts (I). For example, if component "A" controls component "B", there should be a relationship link coded "CAB".
3	Determine the proximate events and analyze components	(1) Find the proximate events in a timeline from the accident report. (2) Analyze the components by determining their responsibilities, safe and unsafe actions, contexts, and mental model flaws.
4	Identify the system's deficiencies	Identify flaws in the control structure as a whole (general systemic factors) that contributed to the loss.
5	Propose the improvement recommendation	Create recommendations for changes to the control structure to prevent a similar loss in the future.

Since all STAMP-derived models, including CAST, are only suitable for qualitative analysis [35,36], to improve the accuracy of the analysis and further weaken the subjective factors of manual qualitative analysis, this paper introduces important quantitative analysis indicators from complex network theory as a supplement to the CAST analysis process.

2.3. System Component Analysis Based on a Complex Network

Complex network theory can quantify and analyze complex systems well, providing a good method for identifying critical nodes in the system. A large number of documents have already applied complex network theory to model and analyze real systems. For example, Shaphari et al. analyzed the fragility of the Iranian power grid using weighted PageRank and identified critical fragile nodes [37]. Zhao et al. analyzed a weighted city infrastructure system network using biased PageRank, reflecting the importance of infrastructure in topology and functionality [38]. Kopsidas and Kepaptsoglou developed a public transportation network with subway stations as nodes and analyzed the importance of nodes using a combination of closeness centrality and betweenness centrality [31]. Tang et al. established a directed weighted network of unsafe behavior in building accidents and analyzed its characteristics using five network attributes: degree and degree distribution, node strength and node strength distribution, average path length and diameter, weighted clustering coefficient, and intermediary degree centrality [39].

In this study, the network formed by system components for a VTA accident scenario can be defined as a "V-T network". The nodes in the network represent the components in the system, while the edges represent their interactions based on the modeled HSCS. Thus, the V-T network is a directed network [37]. The V-T network comprising n nodes and m edges is converted into a directed and weighted graph $G = (V,\ E)$, and the node in the V-T network is represented as $v_n \in V$, while the link in the network is represented as $e_m \in E$.

The weight $w_{i,j}$ of the $e_{i,j}$ is determined by the number of failure controls/feedback $f_{i,j}$ from v_i to v_j according to the statistics from the accident report, as shown in the following formula. The smaller $w_{i,j}$ is, the more fragile the control/feedback relationship is and the closer the distance between v_i and v_j in the network is.

$$w_{i,j} = \frac{1}{1 + f_{i,j}} \tag{1}$$

Then a weighted adjacency matrix $M_{i,j}$ is constructed.

$$M_{i,j} = \begin{bmatrix} w_{1,1} & \cdots & w_{1,n} \\ \vdots & \ddots & \vdots \\ w_{n,1} & \cdots & w_{n,n} \end{bmatrix} \tag{2}$$

Based on this, the impact assessment process of system components is as follows:

Step 1. Analyze network structure features utilizing PageRank (PR). *PR* is a method used to calculate the number of important nodes connected by a node [40]. Typically, the value of PR must undergo multiple iterations before a stable outcome can be reached. This stable outcome serves as the ultimate basis for ranking [41,42]. The *PR* value of node v_i at iteration time t is

$$PR_t(v_i) = \frac{(1-s)}{n} + s\sum_{j=1}^{n} w_{ji}\frac{PR_{t-1}(v_j)}{k_{out}(v_j)} \tag{3}$$

where, $PR_t(v_i)$ is the *PR* of node v_i at time t, s is the random jumping probability, which is usually set around 0.85, w_{ji} is the weight of edge v_j, to v_i, $k_{out}(v_j)$ is the out-degree of node v_j, $PR_{t-1}(v_j)$ is the PageRank value of node v_j at time $t-1$, and n is the total number of nodes in the network.

When the difference between the PageRank values at time t and $t-1$ is less than a specific threshold (i.e., when Equation (4) is satisfied), the iteration is considered to be in a stable state, and the $PR_t(v_i)$ will be the final result.

$$\left|PR_t(v_i) - PR_{t-1}(v_j)\right| \leq \alpha \tag{4}$$

where α is a specific threshold, the value of α = 0.0001 is selected in this paper.

Step 2. Analyze Closeness Centrality (*CC*). In the V-T network, Closeness Centrality is defined as how close a node is to other nodes, usually expressed as the following formula [41].

$$CC(v_i) = \frac{n-1}{\sum_{j\neq i}^{n} g(v_i,\ v_j)} \tag{5}$$

where $CC(v_i)$ is the closeness centrality of the node vi, and $g(v_i,\ v_j)$ is the shortest-path distance between node v_i to v_j.

Step 3. Analyze Betweenness Centrality (*BC*). A higher *BC* means that the influence of a node on the entire network information flow is greater [43–45].

$$BC(v_i) = \sum_{v_s\neq v_i\neq v_t\in V,\ s<t} \frac{\sigma_{st}(v_i)}{\sigma_{st}} \tag{6}$$

where $BC(v_i)$ is the betweenness centrality of node v_i, σ_{st} is the number of the shortest path from the node v_s to v_t, and $\sigma_{st}(v_i)$ is the number of those paths that pass through v_i.

Step 4. Compute Network Importance (*NI*). *NI* is the comprehensive network feature value that combines the above three indicators, representing the influence of a node in the entire network structure.

$$NI(v_i) = \frac{S(v_i)}{\sum_{v_i\in\ V} S(v_i)} \tag{7}$$

$$S(v_i) = \frac{PR(v_i)}{\sum_{v_i\in\ V} PR(v_i)} + \frac{CC(v_i)}{\sum_{v_i\in\ V} CC(v_i)} + \frac{BC(v_i)}{\sum_{v_i\in\ V} BC(v_i)} \tag{8}$$

Step 5. Component Impact (*CI*) assessment. The *CI* represents the contribution of a component to a VTA accident, and its quantitative calculation integrates the *NI* of a component and the proportion of failure control/feedback actions performed by that component.

$$CI(v_i) = log_2\left((NI(v_i) + 1) \times \left(\frac{f_i}{\sum_{i=1}^{n} f_i} + 1\right)\right) \quad (9)$$

3. Case Study

3.1. Stage 1: Initialization

In Stage 1, the accident narrative is completed by extracting valuable information from a VTA accident investigation report [32]. After that, the TSOWF can be defined, and the system hazard and constraints can be identified as the fundamental step of the entire CAST analysis procedure.

3.1.1. Accident Narrative

At 21:00 on 22 August 2017, the vessel Rongxiang 66 of Bohai New Area Rongxiang Shipping Co., Ltd. of Cangzhou, China was carrying 5100 tons from Chi Bay, Shenzhen to the west side of Guishan Pilot Anchorage at the mouth of the Pearl River. At approximately 11:05 on 23 August, affected by super typhoon Hato, the vessel crashed into the base of the #02 wind turbine of the Guishan Offshore Wind Farm in Zhuhai, causing the cargo hold to sink into the water. Eleven people on board fell into the water, including five dead, three missing, and three rescued. The direct economic loss of the accident was approximately CNY 12,460,000. According to the accident investigation report, the causes of this VTA accident included the impact of severe weather and sea conditions caused by super typhoon Hato, the insufficient anchoring position of the vessel to stabilize against the strong typhoon, the insufficient guidance of the vessel safety management system document on typhoon prevention, the insufficient deployment of the master's typhoon prevention work, and the failure to actively enact typhoon prevention measures as early as possible. According to the accident investigation report, Rongxiang 66 had to be held responsible for the accident, and the master was the person responsible for the accident. It can be seen from Figure 3 that the vessel's anchoring position was at the periphery of the anchorage—only 0.8 nm away from the No. 2 pile foundation [32].

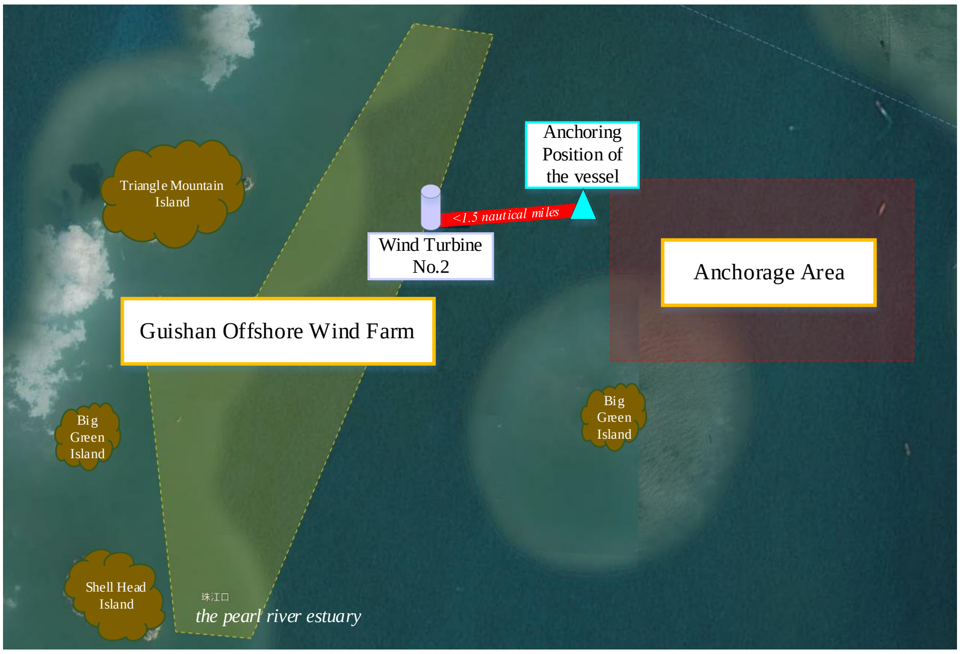

Figure 3. Anchor position of Rongxiang 66 and base position of wind turbine #02.

3.1.2. System, Hazard, and Constraint Definition

In accordance with the basic steps of the application of CAST, the first step is system definition and system hazard identification [46].

1. The traffic system in offshore wind farm water (TSOWF)

Based on the research results of maritime traffic engineering scholars around the world, maritime traffic can be defined as the combination of vessel movements and the overall behavior of vessels in a designated area. Therefore, the maritime traffic system is defined as a dynamic and complex technology environment system involving human control behavior and organizational management roles. The TSOWF can be defined as a collection of various vessel movements and various factors acting on it in offshore wind farm waters. These factors include the water environment, infrastructure, vessels, people who control vessels, and management. The factors change dynamically and interact with each other, thereby jointly determining the dynamic change process of the system state. The system consists of natural environment elements such as hydrology, meteorology, and ocean bottom material, navigation environment elements such as channels, anchorages, ports and wharves, the wind turbines of wind farms, booster platforms, submarine cables, and relevant infrastructure elements of ports and wharves, marine transport vessels, fishing vessels, leisure vessels, engineering vessels, and other vessel elements, as well as crew members, operation and maintenance personnel, supervisors, and other personnel elements.

2. System hazard

According to system theory, not all the functional components in the system operate independently; rather, the components generally interact with each other and undergo dynamic changes in the time and space dimensions. Therefore, the state of the system also changes dynamically. When the stable state of the system collapses, accidents occur. The primary cause of a brewing accident is system hazard. Only by accurately identifying the system hazard can the probability of accidents and losses be effectively reduced [47].

The term "hazard" has many definitions in the field of safety science. It usually refers to the source of danger to a person, property, or the environment. From the perspective of system theory [47], this paper defines the system hazard (*SH*) as a set of hazards (*h*) that may lead to a system collapse:

$$System\ Hazard\ (SH) = \{h_1 + h_2 + h_3 + \cdots + h_n\} \tag{10}$$

The key to analyzing the traffic accidents of offshore wind farms lies in identifying the system hazards of the traffic system of offshore wind farms, as well as in analyzing the structure and mechanism of the system hazards with the help of systematic analysis methods in order to find countermeasures. Based on the direct cause, allision is divided into two types: dynamic allision and nondynamic allision. The former is VTA caused only by human error during navigation [48]. The latter refers to an accident in which the vessel loses control due to equipment failure or the impacts of wind, waves, and currents. Rongxiang 66 VTA can be considered a nondynamic allision. In this case study, two system hazards are mainly identified by the Rongxiang 66 VTA accident report.

System Hazard in Rongxiang 66 VTA accident:

SH1: Vessel anchoring failure caused by wind disasters.
SH2: The vessel is unable to be aware of the OWT on time.

A vessel's stability will decline because of strong wind, waves, heavy rainfall, and other natural environmental factors in the water area, which will result in the vessel going out of control. Because the site selection waters of offshore wind farms are mostly located in areas with abundant wind energy, strong winds and massive waves often occur in these areas. In the Rongxiang 66 VTA accident, Rongxiang 66 was anchored at the arriving route of Super Typhoon Hato. Therefore, one of the system hazards was vessel anchoring failure and dragging caused by strong wind and waves. However, due to the proximity of the wind farm to the anchorage, the TSOWF itself carried a high allision risk. It was too late for Rongxiang 66 to discover the wind farm until it was close enough to collide with the wind turbine. Thus, another system hazard was that the vessel could not be aware of the OWT promptly.

The corresponding system safety constraints are:

SC1: Rongxiang 66 should adopt correct anchoring measures when encountering typhoons.
SC2: Rongxiang 66 could be aware of the position of the Guishan OWF earlier.

3.2. Stage 2: Microanalysis

In Stage 2, a hierarchical safety control structure (HSCS) is designed first to depict and code both the system components and their relationships. A detailed analysis of all the system components is conducted based on the proximate events in the VTA accident and the coded HSCS. Then a V-T network/matrix is constructed and weighted according to the HSCS and the components analysis results. Finally, the multiple network eigenvalues, including *PR*, *CC*, *BC*, *NI*, and *CI*, are computerized to attain the critical components in the TSOWF [49].

3.2.1. Hierarchical Safety Control Structure Design and Coding

The most important step in the STAMP/CAST modeling process is to build a safety control structure, which requires combining expert experience with accident investigation reports to comprehensively display accident-related information as much as possible. In this study, based on the system hazards which are identified in Stage 1, the HSCS is optimized to clearly show the control relationships between system components. First, the system components are classified. The system components are divided into three layers from top to bottom according to man and management (MM), machines and facilities (MF), and environment (E), represented by yellow, blue, and green rectangles. Second, the representation of relationships between components is optimized. Control or feedback relationships are represented by implementation arrows, which are always top-down or left-to-right, while the feedback is the opposite. A dashed line represents a communication relationship between two components, which generally exists only between two components that are not in control of each other. Third, dotted arrows are used to indicate physical impact. The impact can be unidirectional or bi-directional. For example, environmental factors have unilateral effects on the vessel. The allision between the vessel and the wind turbine has a two-way impact, as shown in Figure 4. In order to facilitate component analysis and subsequent complex network analysis, we number both components and control relationships. To facilitate component analysis and subsequent complex network analysis, both components and control relationships are coded. Since only 25 system components are involved in Rongxiang 66 VTA, we code these in capital letters and mark the failure control relationship on the HSCS diagram (Figure 5). The detailed coding matrix can be found in Appendix A.

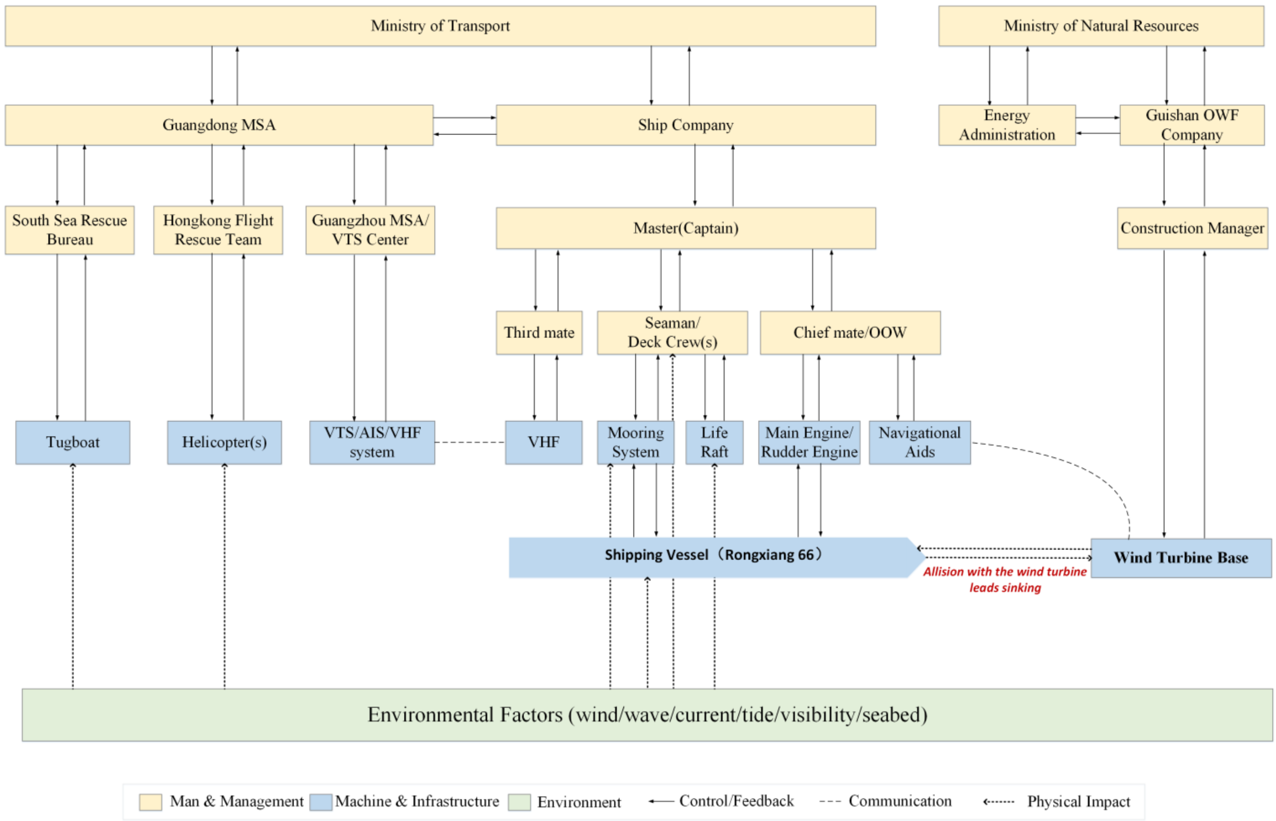

Figure 4. Basic optimized HSCS model.

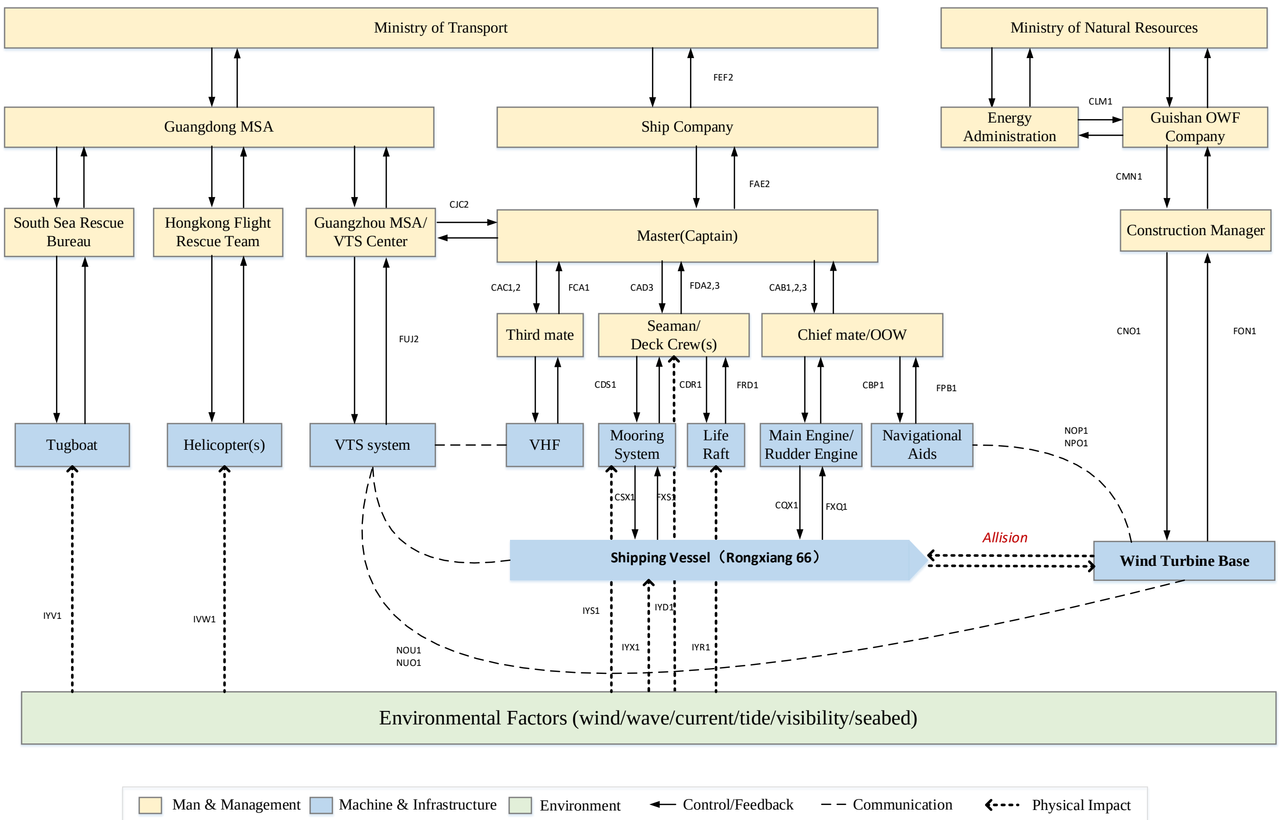

Figure 5. Marked HSCS model.

3.2.2. Proximate Events and System Components Analysis

In this study, the accident proximity events recorded in the accident report are sorted out. Table 2 lists the events on the day of the accident, starting with Hato affecting vessel Rongxiang 66′s stable anchorage and ending with the sinking of the vessel [32]. Based on this detailed analysis of the accident process, we combine Figure 5 to make a detailed analysis of each component of the system, including safety responsibility/basic information, inadequate control/feedback actions, context, and mental/process model flaws, as detailed in Appendix A.

Table 2. Proximate events.

Time	Proximate Events
7:52	Rongxiang 66 began to drag its anchor and move in the southwest direction, drifting at a speed of 1.5 knots.
8:00	Anchor dragging continued. The vessel's drift speed was 1.6 knots, while the northeast wind was at level 8 and the wave height was 2 m. The master and chief mate were on duty at the bridge and began to start the main engine and rudder main to head against the wind.
8:31	Anchor dragging continued. The vessel's drift speed was 1.1 knots, while the northeast wind was at level 9 and the wave height was 3 m.
8:58	The vessel continued to drag anchor, with a drift speed of 1.1 knots, moderate rain, an east wind force of 10, and a wave height of 4 m.
9:38	The vessel continued to drag anchor, with a drift speed of 1.1 knots, heavy rain, an east wind of 11, and a wave height of 4 m.
10:11	The vessel continued to drag anchor, with a drift speed of 2.8 knots, heavy rain, an east wind force of 12, and a wave height of 5 m.
10:28	The vessel continued to drag anchor, with a drift speed of 0.3 knots, a rainstorm, an east wind of 13, and a wave height of 6 m. The master requested to cast the right anchor, but the crew was afraid to go to the bow due to the strong wind and waves
11:00	The vessel continued to drag anchor, with a drift speed of 3.3 knots, a rainstorm, an east wind of 14, and a wave height of 8 m. The master found the vessel approaching the #02 wind turbine base and ordered the crew to report the danger to the shipping company. He ordered the third officer to report the danger to Guangzhou VTS using VHF, and Guangzhou VTS instructed the vessel to take self-rescue measures.
11:05	A VTA occurred and the hull was damaged and flooded. The master reported to Guangzhou VTS and announced the abandonment of the vessel, ordering the first mate to release the life raft, but the life raft was soon blown away by the strong wind after entering the water. The master asked all the crew to assemble at the stern wearing life jackets.
11:10	Rongxiang 66 sank

3.2.3. V-T Network Construction

Based on the component analysis and HSCS diagram, the V-T network and the weighted adjacency matrix (Appendix B) are constructed. The node ID in the V-T network is the same as that in HSCS. The system component label is shown on each node in the diagram in Figure 6. The higher the proportion of incorrect actions is, the lower the weight is and the thinner the lines on the chart are, implying that the link is more fragile. The diagram shows that the master is in the central position with a higher error rate, followed by the chief mate and third mate, which also corresponds to the conclusions of the accident investigation report. The OWF construction managers also show a high error rate. Regarding marine management, there are some problems in the communication and coordination of the Guangzhou VTS center. Moreover, the vessel and all crews were heavily affected by typhoon Hato, while neither the vessel nor the VTS center detected the wind turbine.

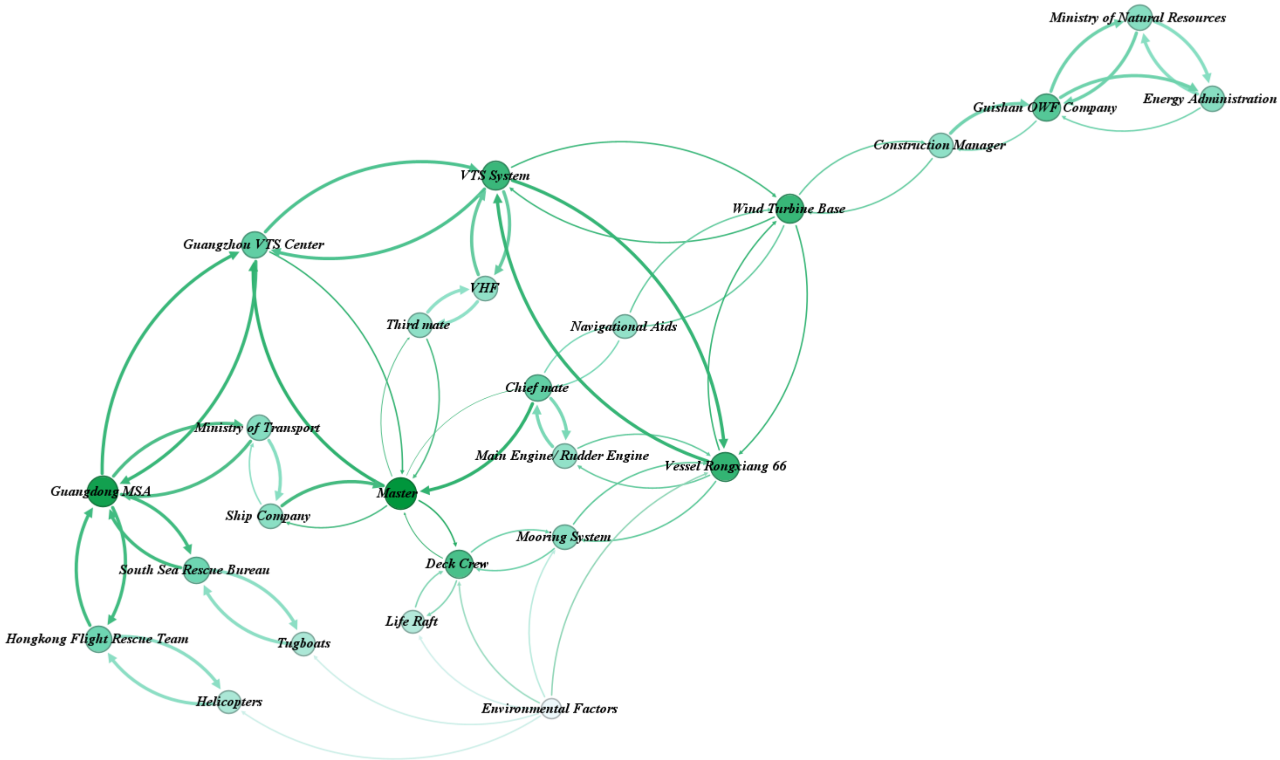

Figure 6. Diagram of the V-T network.

3.2.4. Critical Node Analysis

Based on the V-T network/matrix, the PR, CC, and BC of the network nodes are calculated. The results are displayed in Appendix C. The PR (0.0745) of the master ranks first, indicating that the master has connected more important nodes in the whole system. As the first person in charge of ship safety, the master is indeed the most important role and the most important component of the system in this accident. The highest CC (0.4) ranking is the environmental factor, indicating that the node affected by the environmental factor has the most problems. This also corresponds to the actual situation in that typhoon Hato causes a series of events after Rongxiang 66's anchoring. The highest BC (0.3496)-ranked Guangzhou VTS center is the front-line unit of traffic management because the VTS center should coordinate vessels and report to senior management in a timely fashion. Based on the above three eigenvalues, the normalized network importance (NI) is calculated. The results of NI uncover that the maritime management departments, including the MSA, VTS center, and VTS system, have a high degree of importance in the network model, which indicates the 24/7 vessel traffic service the departments provide and the important command and coordination role they play in emergency response after accidents occur. The calculation results of component impact obtained by superimposing the network importance and component failure ratio are shown in Figure 7. The top ten components account for 71.5% of all component impacts on this VTA accident, so they are regarded as critical components. The master, wind turbine base, environment, deck crew, and VTS center rank higher. The master holds a high level of importance in the network because he undertakes the safety management, typhoon prevention, and emergency evacuation decision-making functions of the vessel and crew. Obviously, in this accident, the master also has an unshirkable responsibility. Meanwhile, of environmental factors having a wide and serious impact on vessels and crew, almost all were triggered by super typhoon Hato. The analysis result of above system components or factors is basically consistent with the causation analysis in the accident investigation report.

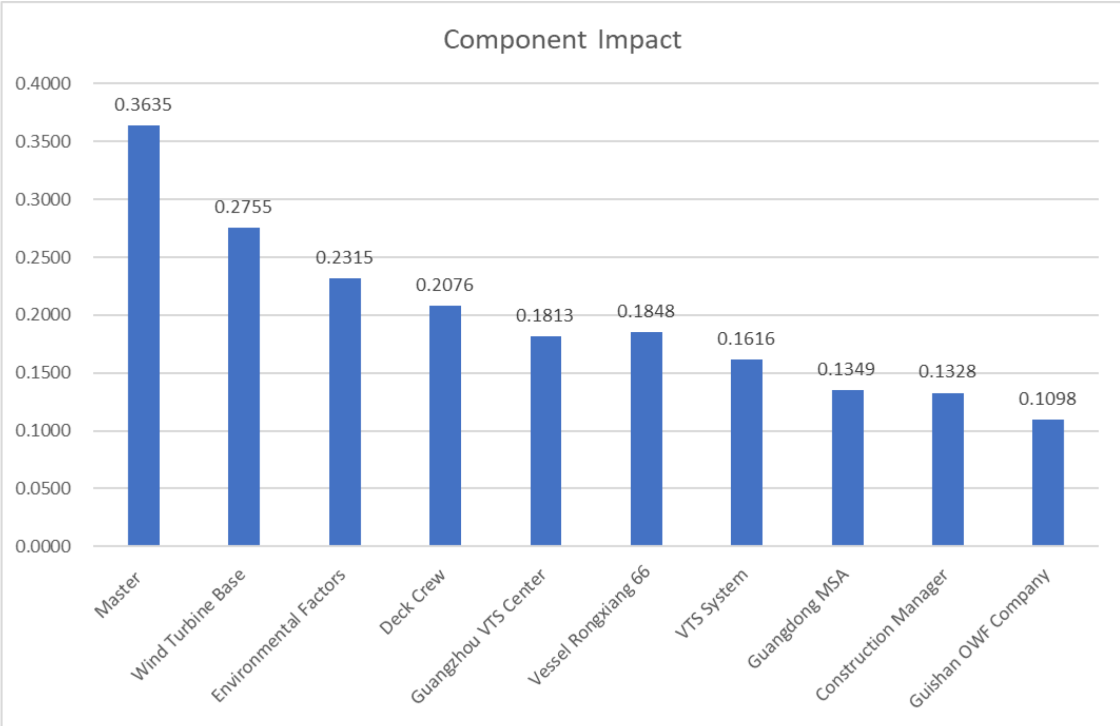

Figure 7. Rank of the component impact.

However, components related to OWF and MSA, which have no fault according to the accident report, play a significant role in the accident impact in this study. For instance, the components related to wind farms, such as wind turbine base, construction managers, and operating companies, played critical roles in this VTA accident, but the accident investigation report did not conduct an in-depth analysis of them, only introducing basic information about the wind farm. The results of this analysis confirm the core philosophy of Leveson's design of STAMP and CAST, which is not to pursue accountability but to improve system safety. This brings more enlightenment in that the dynamic process and safety of the VTA system need to be analyzed from a higher level.

3.3. Stage 3: Macroanalysis

In Stage 3, the system deficiencies in the VTA accident are identified, and improvement recommendations are proposed.

3.3.1. System Deficiency Identification

At the macro level, both internal and external factors of the system will affect each system component [31]. Among them, the internal factors from the surface to the core of a system can be divided into four levels, which are communication and coordination, the safety information system, safety management, and safety culture, as shown in Figure 8. These internal factors are influenced layer by layer. Meanwhile, external factors, including the economy, policy, and environment, are independent of each other and simultaneously generate impact to the system, leading to the occurrence of system deficiencies.

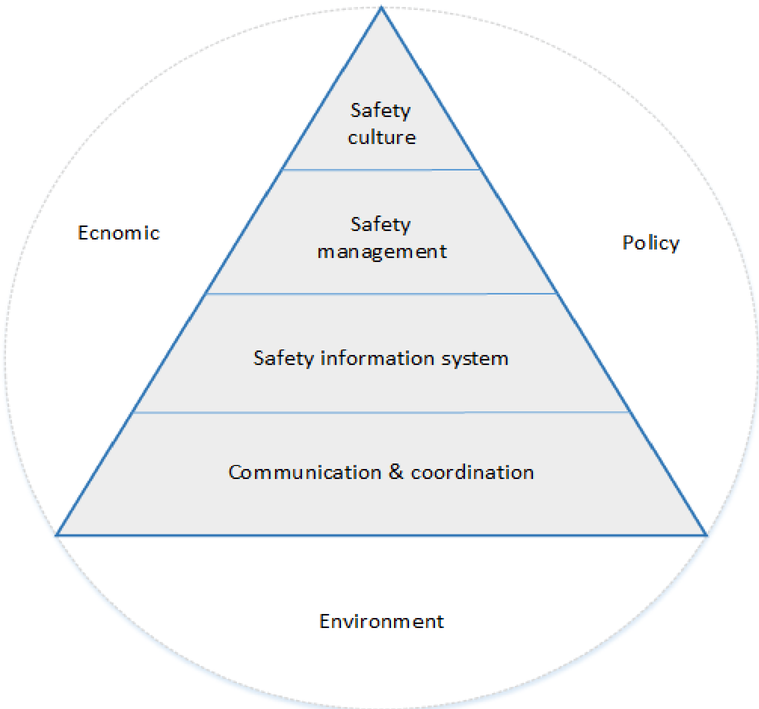

Figure 8. Overall system safety architecture on the macro scale.

Through a CAST-CN analysis of the Rongxiang 66 accident, system defects can be identified based on the above aspects. The limited system defects are explained in the accident report. This study will be further improved or corrected.

1. Internal factors

Communication and coordination: In this case, Figure 5 shows the physical communication or sensing links established at four system levels based on communication and sensing devices, such as VHF, AIS, radar, and CCTV, with the following dotted lines:

NUX (NXU): Sensing link between vessels and VTS system.
NTU (NUT): Communication link between the VTS system and VHF on the vessel.
NOP (NPO): Sensing link between shipborne navigation system and turbine.
NUO (NOU): Sensing link between VTS system and turbine.

Ideally, these links should remain unblocked. Communication between the VHF and VTS systems on board is normal, and Rongxiang 66 can also be found by the VTS system in the accident report; however, there is no reference as to whether the VTS and on-board auxiliary navigation systems can detect wind turbines in wind farms. However, in this accident, the master or any other crew did not perceive the existence of any facility in the OWF through any measure prior to the appearance of the wind turbine in the field of vision, and the VTS center did not indicate the existence of the OWF. Therefore, it can be inferred that the two links of NOP and NUO are abnormal. The abnormal link is probably caused by either no AIS terminal being installed in the infrastructure of the wind farm or the AIS terminal being incorrectly used or faulty after installation, which means that the vessel or VTS system fails to receive AIS signals. It is also possible that the inadequate precision of the VTS system's radar and ship-borne radar or the existence of blind areas leads to the inability of vessels or the VTS system to actively detect wind farm infrastructure.

Hence, at the system level, effective communication and coordination between the wind farm, ship, and VTS center are missing, which is one of the most significant causes of accidents but is not analyzed in the accident report.

Safety information system: A safety information system is an important human–machine interaction intermediary in a complex system. In this case, both shipping companies and offshore wind farm operators have safety information systems, but there is very little information sharing between these systems. As can be seen from Figure 5, there is no communication channel between them, especially between the Ministry of Natural Resources, which is the top management department of the offshore wind farm company, and the Ministry of Transport, which is the top management department of the shipping company. Shipping companies lack clarity about the construction of offshore wind farms in operating waters and it is difficult for offshore wind farm operators to master the dynamics of nearby vessels. Therefore, there are problems with the safety information system throughout the system. This reason is not analyzed in the accident investigation report.

Safety management: Effective safety management is a guarantee for the implementation of a system safety operation mechanism. In this case, the insufficient guidance of a shipping company regarding the anchorage of a vessel's platform is an obvious safety management problem. The inadequate training of the crew results in various erroneous operations, such as the life raft being blown away by the wind after being released, which also reflects the insufficient safety management of the shipping company. In addition, the location of the Guishan offshore wind farm is less than two miles from the pilot anchorage and five miles from the main channel, which is the busy traffic area in the Pearl River Estuary. The wind power infrastructure is likely to affect navigation vessels or interfere with VTS, CCTV, and other systems of the Maritime Bureau. The problems existing in the site selection also reflect the lack of scientific and accurate demonstration by the energy and transportation departments. Finally, the design of structural toughness, anti-collision facilities, and anchor chain strength of the vessel Rongxiang 66 may not match the power of the super typhoon Hato, which leads to the low fault tolerance rate of the driver once the ship falls into this extreme environment. However, the above problems are safety management problems at the whole scale of complex systems. Although there are some safety management suggestions in the accident report, they are not all discovered, and the deeper reasons are not analyzed.

Safety culture: Safety culture is the core of safety management. Specifically, the defectiveness of safety awareness of some enterprise managers will lead to an unsafe cultural ecology of an entire organization. Leveson lists five elements of a safety culture in the CAST manual: Culture of Risk Acceptance, Culture of Denial, Culture of Compliance, Paperwork Culture, and Culture of Swagger. Through our preliminary analysis, these five unhealthy safety cultures have been reflected to some extent in this case. For example, the safety culture of shipping companies is defective. First of all, the precondition for the accident was extreme weather. Before the typhoon approached, the shipping company did not promptly let ship Rongxiang 66 find a safe harbor to anchor but rather let it wait for work in the harbor area. Secondly, when the vessel left the harbor in search of anchorage platforms under the instructions of the VTS center, the shipping company only sent some typhoon information searched on the internet and the company's defense documents (defective). These aspects demonstrate the company's culture of Risk Acceptance, which values productivity while ignoring safety issues. Similarly, in OWF companies, the lack of site selection considerations, based more on the perspective of their operating interests, does not establish adequate safety awareness systems; it only meets the basic government requirements. These also reflect the existence of the culture of Compliance, Paperwork Culture, and other unsafe cultures in the OWF companies.

2. External factors

Additionally, there are three external factors affecting the system: economy, policy, and environment. These external factors are inherently uncertain and can influence a complex system to produce dynamic changes.

Environmental factors: Uncertainty of the environment is one of the main factors of navigation risk of vessels. The system analyzed in this VTA case is severely affected by environmental uncertainties. The factors such as wind, waves, currents, and visibility can have impacts on the stability of ships and the decision-making ability of crew members. These environmental factors, which are rapidly changeable in extreme weather such as typhoon Hato, are difficult to predict accurately. In addition, the path of the typhoon may reroute, and the impact range may also enlarge over time, which will challenge the prevention plan of the master and ship company. Therefore, if the system resilience is not enough to deal with the uncertainty of environment, it is necessary to keep as far away as possible from waters with typhoon activity during the actual voyage and to take relevant measures as early as possible.

Economic factor: In recent years, the revival of the Chinese shipping industry has made maritime vessel traffic busier. To obtain high profits, many shipping companies have chosen to reduce the safety standards of production and operation. These companies can reduce the cost of investment in safety, and they can loosen production and make it develop quickly without restrictions. This has reduced the requirements for ship quality and crew quality, resulting in higher safety risks.

Policy factor: The offshore wind power subsidy policy issued by the Chinese government lasts until 2022, so a large number of offshore wind farms have been constructed with great haste in recent years, which has resulted in a possible lack of safety assessment from site selection to design of facilities. The guiding force of this policy is intended to help accelerate the development of China's offshore wind power industry. However, this policy has also generated a reacting force that leads OWF companies develop wind power resources by all means covered and has hidden some safety hazards.

3.3.2. Improvement Recommendations

Based on the results of the above analysis, we provide the following system improvement recommendations.

1. Overall planning of marine traffic resources

Conflicts concerning the use of marine resources between marine traffic and wind power generation are one of the primary causes of VTA accidents, and require macro and long-term planning. At the stage of planning and site selection for offshore wind farms, relevant port, shipping, and maritime institutions should intervene in advance, strengthen coordination with development and reform, energy, natural resources, and other departments, and actively participate in the formulation and revision of territorial and spatial planning, such as marine functional zoning, to ensure marine transportation resources.

2. Establishing the OWF traffic safety management coordination mechanism

Following the Chinese safety-relevant laws, regulations, and the division of responsibilities, the transportation department should establish and improve the cooperation mechanism of joint law enforcement, supervision, and management with other competent departments in the industry, clarify the government regulatory responsibilities of the energy and transportation departments, strengthen the safety supervision of the offshore wind farms throughout their life cycle, and construct a dual prevention mechanism for hierarchical risk management and control of OWF safety and the investigation and treatment of potential accidents.

3. Simultaneous construction of sufficient navigational safety facilities

In conformity with relevant Chinese laws and rules on work safety, safety facilities for production, operation, and construction projects must be designed, constructed, and operated simultaneously with the main works. Because of the problems existing in the traffic safety management in OWF waters, the owner of an OWF should strengthen the construction of early-warning safety facilities and carry out special research on the impact of wind farm construction on offshore regulatory facilities. Relying on the infrastructure of an OWF, radar, surveillance cameras, and other sensing equipment for vessels should be constructed to improve the coverage of the maritime safety supervision system.

4. Strengthening the construction of maritime supervision and rescue capacity

An offshore wind farm is usually located in an unshielded sea area rich in wind energy. The navigation environment is relatively harsh, and the requirements for the ability for regulatory search and rescue equipment are high. It is necessary to increase the configuration scale of rescue aircraft and improve equipment performance.

4. Discussion

The innovation of this study mainly lies in applying the method of system theory analysis of accidents to special cases of allisions between vessels and wind turbines in OWF waters, which has been rarely performed in previous research. Second, we optimize the CAST method in STAMP and divide the analysis process into three stages: initialization, microanalysis, and macroanalysis, making the analysis clearer, more targeted, and easier to combine with other methods. In addition, to make up for the shortcomings of the STAMP method in quantitative analysis, we integrate the analysis process of complex networks and establish a network model and matrix based on the HSCS constructed by STAMP. We analyze the PR, CC, BC, NI, and CI of each component in the VT network, and the results meet expectations.

The practical implication of this study is based on an accident in the waters of an offshore wind farm. The analysis results obtained through optimization methods are consistent with the accident report, confirming the scientific nature of the method itself, and can be used as a tool for subsequent analysis of such systems. In addition, other factors not analyzed in the accident report are identified, especially regarding communication perception, safety management, and safety culture in the macroanalysis process, as well as the contribution of external economic and policy factors to the occurrence of accidents. Therefore, the analysis method discussed in this article can serve as a powerful supplement to accident investigation, making the results of an accident investigation more scientific and reversing the long-standing responsibility-oriented analysis approach, providing support for the true improvement of system safety.

Admittedly, there is still considerable scope for improvement in this study. For example, there could be a deeper understanding of the case in terms of data acquisition. Relying solely on accident investigation reports and some data information searched online cannot accurately restore the appearance of the accident itself. If the real-time data from vessel tracking systems, weather monitoring, and offshore infrastructure sensors could be integrated into the analysis, the accuracy and timeliness will be enhanced significantly. Future research could explore methods to collect and analyze such data to improve the understanding of offshore wind farm water transportation system safety. Secondly, the method of complex networks only analyzes some basic indicators, which can be further applied to other analysis methods such as the percolation on complex networks.

5. Conclusions

Given the stimulus of the subsidy policy of the Chinese government, offshore wind power has grown at an incredible speed. Many dynamic complex systems composed of vessels and OWF have been formed in a short time, which has caused new navigational safety problems. Due to the characteristics of rare accident cases, incomplete accident data, and dynamic nonlinearity, it is difficult to use traditional data statistics and event chain analysis methods to find the critical factors of a VTA accident. In this study, CAST, in the STAMP family, is utilized, and the complex network theory and method are combined to analyze the accident case of Rongxiang 66 colliding with a wind turbine qualitatively and quantitatively for the macro and micro levels of the system. The main contributions of this study are as follows:

- A typical VTA accident between a vessel and a wind turbine in the navigation system of offshore wind farm waters is systematically analyzed, which establishes the effectiveness of the STAMP model in solving this kind of complex system. In addition, the model design of the safety control structure is improved, and the CAST-CN analysis model is constructed based on the CN, which creatively compensates for the blanks in the quantitative analysis of the cast, and enhances the scientific quality and accuracy of the accident analysis.

- The combined macro and micro analyses of accidents reveal some key factors not mentioned in the accident report, such as maritime traffic management and OWF operation management, which are of great significance to improve navigational safety.

Nevertheless, the CAST-CN model has great potential for improvement; for example, it can be adapted for various types of accidents and network analysis methods. The analysis of different types of offshore wind farm water accidents based on the CAST-CN model will help maritime departments and relevant research organizations gain a comprehensive understanding of the safety problems and key factors of offshore wind farm water transportation system so as to improve the safety of the system. Future research could delve deeper into understanding the perspectives and roles of various stakeholders involved in these systems, such as vessel operators, wind farm operators, regulatory authorities, and coastal communities. This would allow for a more comprehensive analysis of the factors influencing safety and the development of targeted recommendations for each stakeholder group.

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Appendix A. Component Analysis Based on HSCS-Marked

Table A1. Component analysis results.

Component	Safety Responsibility/Basic Information	Inadequate Control/Feedback Actions	Context	Mental/Process Model Flaws
Master (Captain)	Superior responsibility for safe ship operation and implementation of the safety management system onboard.	CAB1. Issue an order to proceed to the Guishan Pilot Anchorage for typhoon protection. CAB2. Issue the command to use the rudder to withstand the wind after the vessel loses anchor. CAB3. After discovering the wind power base, order OOW to report the danger to the shipping company. CAC1. Command the third officer to strengthen listening to the typhoon information released by VTS. CAC2. After discovering the wind power base, order the third officer to report the danger to Guangzhou VTS center. CAD3. After the anchor pulling occurs, when the wind reaches levels 12–13 and the wave height is 6 m, the command to add the right anchor is issued. FAE2. Deployment of typhoon prevention does not fully meet the requirements of the plan.	1. Encounter extreme conditions—Typhoon Hato; 2. Have experience as a master; 3. Have a certificate of ship management; 4. Recently, the master received safety training from the company; 5. Time lag.	1. Insufficient safety awareness: a comprehensive typhoon prevention plan was not formulated as early as possible, and even waiting for operations in the open waters of the wharf before the typhoon hit; when the VTS center reminded the ship to come and prepare for typhoon prevention, the wrong typhoon prevention anchorage was selected (located in the center of the typhoon); 2. Poor perception: lack of mental preparation for the impact of typhoons and the uncertainty that may change their path; the situation of the surrounding waters is not fully understood, and it is not clear that there are wind farms. 3. Poor emergency decision-making ability. After the anchor slip occurred, there was no choice but to add dual anchors on time, and only applicable to the rudder power against the wind. When the wind reaches 12–13, it is too late to require sailors to add dual anchors. 4. Poor communication skills, failing to report to the company and VTS on time after a breakout occurred, and not reporting until the risk of collision with the wind turbine was discovered.

Table A1. *Cont.*

Component	Safety Responsibility/Basic Information	Inadequate Control/Feedback Actions	Context	Mental/Process Model Flaws
Chief mate/OOW	The chief mate is second in command to the Master, a head of the deck department and, customarily, an officer in charge of the vessel's cargo and deck crew. Officer of the watch(OOW) steers the vessel/keeps watch on the bridge.	CBP1. It is unknown whether to use radar/AIS or other means to observe wind turbine facilities in nearby waters.	1. Encounter extreme conditions—Typhoon Hato; 2. Have shipmate experience; 3. Have a competency certificate for crew members; 4. Recently received safety training from the company.	1. Poor perception: lack of mental preparation for the impact of typhoons and the uncertainty that may change their path; the situation of the surrounding waters is not fully understood, and it is not clear that there are wind farms.
Third mate	The third mate is a watchstander and, customarily, the vessel's safety officer, focusing on firefighting equipment, lifeboats, and various other emergency communication systems.	FCA1. Failing to report the VTS broadcast typhoon prevention suggestions to the master as soon as possible.	1. Encounter extreme conditions—Typhoon Hato; 2. Have shipmate experience; 3. Have a competency certificate for crew members; 4. Recently received safety training from the company; 5. Time lag.	1. Lack of responsibility and safety awareness: when listening to the VTS broadcast, because the VTS did not mention Rongxiang 66, it did not immediately report the typhoon prevention suggestions to the master.
Seaman/Deck Crew	Crewmembers looking after safety in accommodation, public areas, cargo, and other areas. Guarantee the safety of navigation and the maintenance of vessels.	FDA 2. Due to the strong wind and waves, the master's order to add the right anchor was not implemented. FDA 3. The command to release the lifeboat was not effectively implemented due to the strong wind and waves. CDR1. The lifeboat was not released correctly, resulting in the lifeboat being blown away by the wind. CDS1. After the vessel anchored, due to the strong wind and waves, the right anchor was not added.	1. Encounter extreme conditions—Typhoon Hato; 2. Have crew experience; 3. Have a competency certificate for crew members; 4. Experienced safety training from the company.	Inadequate safety awareness and emergency skills: in the case of heavy winds and waves, the deployment of lifeboats failed.

Table A1. *Cont.*

Component	Safety Responsibility/Basic Information	Inadequate Control/Feedback Actions	Context	Mental/Process Model Flaws
Ship Company	Responsible for ship safety management, organizing regular safety risk assessment and hidden danger inspection for vessels, and regular safety training for crew members.	FEF2. The content of the safety management system document "Instructions for Ship Anti Taiwan" is not standardized.	1. Obtain typhoon information through the Internet; 2. Time lag.	There are loopholes in the safety management system: the formulated typhoon prevention documents do not stipulate that the master should study and deploy the vessel's typhoon prevention work, and do not stipulate that the vessel closely tracks the typhoon dynamics; there is no regulation that companies should also track typhoon dynamics and deploy guidance for ship typhoon prevention work.
Guangzhou MSA/ VTS Center	Unified management of water traffic safety and prevention of ship pollution, management of navigation order, and navigation environment, and is responsible for the management of ship and marine facilities inspection industry, as well as ship seaworthiness and ship technology management, etc.	CJC2. No anchorage suitable for typhoon prevention is recommended.	1. Encounter extreme conditions—Typhoon Hato; 2. Have 24 h duty personnel; 3. Keep a close track of typhoon dynamics.	
Energy Administration	Departments that manage natural energy, responsible for the approval of offshore wind farm site selection and construction.	CLM1. Review of offshore wind farm sites and construction plans.	Unknown.	1. The review of offshore wind farm construction plans was not rigorous.

Table A1. *Cont.*

Component	Safety Responsibility/Basic Information	Inadequate Control/Feedback Actions	Context	Mental/Process Model Flaws
Guishan OWF Company	Responsible for the construction and operation safety management of offshore wind farms.	CMN1. Manage and guide the construction manager of offshore wind farms (inadequate).	1. Obtained a sea area use right certificate; 2. The wind farm built is only 1.5 nautical miles from the east anchorage, only 0.88 nautical miles from the southern anchorage, and only 1.36 nautical miles from the high-speed passenger ship route; 3. LED light warning signs are set according to the Navigation Safety Assessment Report.	1. There are defects in the site selection scheme for offshore wind farms, resulting in significant conflicts with traffic and sea use. 2. Lack of safety awareness. Only the LED warning means recommended in the Navigation Safety Assessment Report are used, without any other supplementary means. When encountering severe weather, this means is insufficient.
Construction Manager	The main responsible person for work safety during the construction of offshore wind farms, fully responsible for the construction safety of wind farms.	CNO1. Ensuring the safe construction and operation of wind turbines (insufficient).	1. Encounter extreme conditions—Typhoon Hato.	1. Lack of safety awareness. Increase safety protection for wind farms before responding to typhoons in advance.
Wind Turbine Base	The base load-bearing structure used to support the wind turbine.	FON1. During the construction process, there are no communication links and technical means to provide feedback; NOP1. Whether it can be detected by radar or AIS means is unknown; NOU1. Whether it can be detected by radar or AIS means is unknown.	1. LED light warning signs are installed.	1. Lack of AIS terminals, unable to be perceived; 2. Lack of ship collision prevention facilities; 3. Lack of early warning systems such as electronic fences.
Navigational Aids	Using radar, ECDIS, AIS, and other techniques, helps the crew to perceive the surrounding obstacles and ships and provide decision-making guidance equipment for navigation.	FPB1. It is unknown whether the information on surrounding ships/offshore structures can be displayed normally; NPO1. It is unknown whether the fan base can be detected.	1. Normal operation.	Lack of a ship wind turbine collision warning model: it is not possible to give an alarm when a ship approaches the waters of an offshore wind farm.

Table A1. *Cont.*

Component	Safety Responsibility/Basic Information	Inadequate Control/Feedback Actions	Context	Mental/Process Model Flaws
Main Engine/Rudder Engine	Provide propulsion power to the vessel and drive the propeller. Provide the vessel with slewing torque to keep the vessel on the course or to turn.	CQX1. Provide ship power (insufficient).	1. Encounter extreme conditions—Typhoon Hato.	
Life Raft	Special boat on board for rescuing people overboard or evacuating people when the vessel is in distress.	FRD1. Loss of control after release into the sea.	1. Encounter extreme conditions—Typhoon Hato.	
Mooring System	Equipment used to fix the vessel when it is moored, including anchor, anchor chain, and anchor machine.	CSX1. Provide anchoring control (insufficient).	1. Encounter extreme conditions—Typhoon Hato.	
VTS System	The system used by the MSA to manage the order of ship navigation.	NUO1. It is unknown whether the fan base can be detected; NUX2. Failed to provide early warning of vessel collision with wind turbines; FXQ1. Not fully controlled by the rudder system; FXS1. Anchor dragging occurs.	1. Normal operation.	1. Lack of intelligent aided decision-making model: unable to provide detailed suggestions on typhoon prevention schemes for each ship; 2. Lack of a ship wind turbine collision warning model: it is not possible to give an alarm when a ship approaches the waters of an offshore wind farm.
Rongxiang 66	The vessel that sank in this case, a dry cargo ship, with a total length of 98.6 m, a total tonnage of 2879 tons, a deadweight of 5385 tons, and a main engine power of 1545 kW, was completed in 2004.		1. Encounter extreme conditions—Typhoon Hato.	

Table A1. *Cont.*

Component	Safety Responsibility/Basic Information	Inadequate Control/Feedback Actions	Context	Mental/Process Model Flaws
Environmental Factors	In this case, the environmental factors are mainly the strong winds and waves caused by typhoon Hato, with the maximum wind force reaching 15, the wave height reaching 10 m, and the moving path changing several times. In addition, the anchorage of the Rongxiang 66 anchor is a pilot anchorage, and the seabed sediment cannot provide sufficient anchor grip.	IYD1. When the wind force of Typhoon Hato reached Force 12, the crew was unable to carry out anchoring operations on the deck; IYR1. The strong wind blew away the rescue boat; IYS1. The seabed bottom material cannot provide sufficient anchor grip; IYV1. Severe weather affects rescue speed; IYX1. Heavy winds and waves caused the vessel to lose control.		

Appendix B. The Weighted Matrix of V-T Network

Table A2. V-T matrix with edge weights.

ID	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*	*M*	*N*	*O*	*P*	*Q*	*R*	*S*	*T*	*U*	*V*	*W*	*X*	*Y*
A		0.25	0.333	0.5	0.5					1															
B	1															0.5	1								
C	0.5																			1					
D	0.333																	0.5	0.5						
E	1					0.5																			
F					1		1																		
G						1		1	1	1															
H							1																1		
I							1															1			
J	0.5						1														1				
K												1	1												
L											1		0.5												
M											1	1		0.5											
N													1		0.5										
O														0.5		0.5					0.5			0.5	
P		0.5													0.5										
Q		1																						0.5	
R				0.5																					
S				0.5																				0.5	
T			1																		1				
U										1					0.5					1				1	
V									1																
W								1																	
X															0.5		0.5		0.5		1				
Y				0.5														0.5	0.5			0.5	0.5	0.5	

Appendix C. Network Analysis Result of CAST-CN

Table A3. Network analysis results (*PR*, *CC*, *BC*, *NI*).

ID	Label	*PR*	*CC*	*BC*	*NI*
A	Master	0.0745	0.3710	0.2681	0.086
B	Chief mate	0.0452	0.3382	0.0857	0.037
C	Third mate	0.0322	0.3067	0.0199	0.018
D	Deck crew	0.0526	0.3151	0.1172	0.045
E	Ship company	0.0335	0.2987	0.0314	0.021
F	Ministry of Transport	0.0349	0.2840	0.0181	0.017
G	Guangdong MSA	0.0690	0.3333	0.3219	0.098
H	South Sea Rescue Bureau	0.0415	0.2584	0.0812	0.033
I	Hong Kong Flight Rescue Team	0.0415	0.2584	0.0812	0.033
J	Guangzhou VTS Center	0.0455	0.3966	0.3496	0.105
K	Ministry of Natural Resources	0.0346	0.1933	0.0000	0.010
L	Energy Administration	0.0346	0.1933	0.0000	0.010
M	Guishan OWF company	0.0491	0.2347	0.1558	0.051
N	Construction manager	0.0321	0.2875	0.2228	0.068
O	Wind turbine base	0.0576	0.3594	0.3110	0.095
P	Navigational aids	0.0310	0.3067	0.0374	0.023
Q	Main engine/rudder engine	0.0314	0.2949	0.0100	0.015
R	Life raft	0.0218	0.2421	0.0000	0.010
S	Mooring system	0.0343	0.2987	0.0531	0.027
T	VHF	0.0318	0.3108	0.0254	0.020
U	VTS system	0.0572	0.3898	0.2859	0.090
V	Helicopters	0.0245	0.2072	0.0033	0.010
W	Tugboats	0.0245	0.2072	0.0033	0.010
X	Vessel Rongxiang 66	0.0592	0.3538	0.1443	0.054
Y	Environmental factors	0.0060	0.4000	0.0000	0.014

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