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Research on Coupling Mechanisms of Risk Factors for Collision Accidents Between Merchant Ships and Fishing Vessels Based on the N-K Model

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Abstract: Preventing collision accidents between merchant ships and fishing vessels has long been a significant challenge for maritime safety in coastal waters. To quantitatively analyze the relationship between the risk factors contributing to these collisions, identify the key factors leading to such accidents, and develop effective prevention strategies, the N-K model was employed to examine the risk coupling mechanisms involved. The model was based on an analysis of 132 collision incidents between merchant ships and fishing vessels in China's coastal waters from 2013 to 2023. The characteristics of these collision accidents were investigated, and the risk factors were categorized into four distinct types: human, management, environmental, and ship factors. The coupling of collision risk factors between merchant ships and fishing vessels was mainly considered from the perspective of the overall system, and the N-K model was used to calculate the probability and risk values associated with the coupling of these four risk factors. Modeling results indicated that the coupling value of four factors was 0.1083, which was 1.5 times greater than the maximum coupling value of three factors and 2.1 times greater than the maximum coupling value of two factors. The risk of collision accidents between merchant ships and fishing vessels increases gradually with an increase in the risk coupling factors. Among the four categories of factors, the risk coupling between the ship factors and environmental factors is associated with a relatively large probability of accidents. Appropriate countermeasures were proposed to implement effective preventive measures at the source of collision accidents.

Keywords: merchant ships; fishing vessels; collision accidents; N-K model; risk coupling

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1. Introduction

Since the 1980s, global fishery production has fluctuated within the range of 86–94 million tons per year. In 2022, fishery production reached 92.3 million tons (worth USD$159 billion), of which 79.7 million tons came from marine fishery production, accounting for 86% of the total fishery production [1]. Marine fishing remains a major source of global fish consumption; thus, marine fishing activities play a crucial role in global food and nutrition security. Approximately 260 million people are engaged in fishing activities worldwide, and fisheries are one of the most important sectors providing employment opportunities for over 100 million people [2]. Many fishing communities live alongside seashores, and their livelihoods have relied on deep-sea fishing for several generations. Although marine fishing activities are very important, they are associated with significant risks. Marine fishing is considered a risky profession in terms of economic benefits, occupational injury, and fatality [3–5]. Marine fishing is one of the most dangerous occupations,

with high mortality; on an average, 24,000 fishermen die annually as a result of accidents [6]. The estimated fishing fatality rate of 80 deaths/100,000 individuals per annum is 79 times higher than the overall occupational fatality rate [7]. According to the 2019 NIOSH (National Institute for Occupational Safety and Health) Commercial Fishing Incident Database, commercial fishing has consistently ranked as one of the most hazardous occupations in the United States. Marine fishing is one of the professions with the highest number of employee casualties worldwide. Therefore, marine fishing accidents represent a global challenge [8].

As the world's largest fishery producer, China has abundant fishery resources with its gross production playing an important role in the national economy. According to data from the National Bureau of Statistics, the total output of China's fishery industry has shown a continuous growth trend over the past decade. As shown in Figure 1, in 2023, China's total fishery output value reached CN¥1.6 trillion, with approximately 3.6 million tons of marine-based products. Fishing vessels are important production tools that are closely related to fishery development. According to the 2023 National Fishery Economic Statistics Bulletin, the total number of Chinese fishing vessels in 2023 was 496,500, including 338,800 motorized fishing vessels. In recent years, significant progress has been made in the maneuverability and navigation equipment of fishing vessels; however, the safety issues of fishing vessels remain prominent. In addition to fishing vessels, many commercial ships also sail along the coast of China. Recently, the number of mobile merchant ships and fishing vessels in China has decreased (Figure 2). In 2023, the number of mobile merchant ships and fishing vessels in China was 110,000 and 338,800, respectively. With the increase in the number of merchant ships navigating along the Chinese coasts and the activities of fishing vessels, collision accidents between them have become frequent in areas where merchant ships and fishing vessels intersect and overlap, particularly in densely navigable areas and during intense fishing periods [9,10]. The collision accident between merchant ships and fishing vessels has become one of the maritime traffic issues of great concern to the Chinese government.

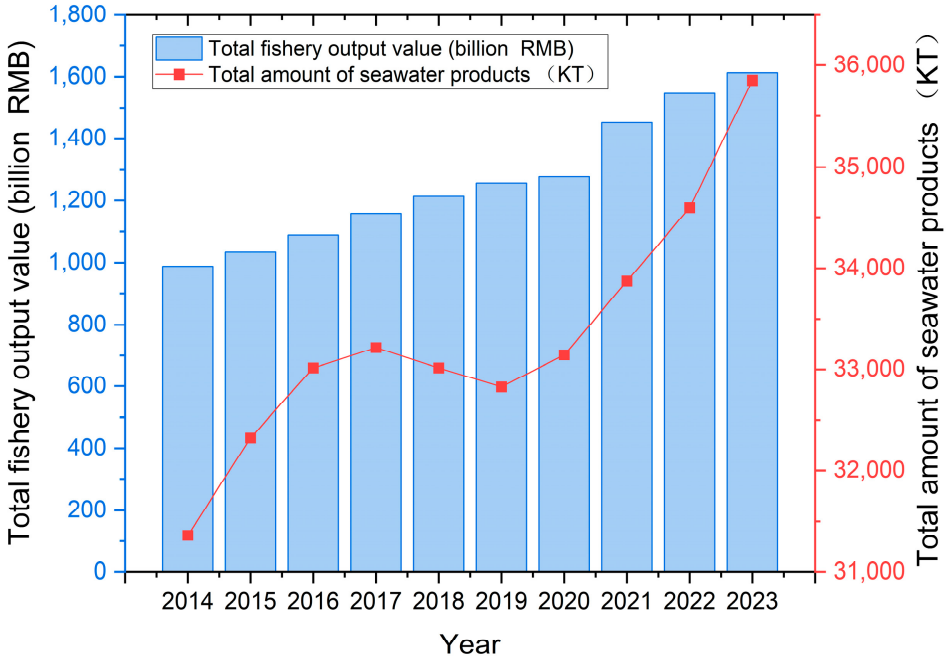


Figure 1. Total fishery production value and total amount of marine products produced in China from 2014–2023.

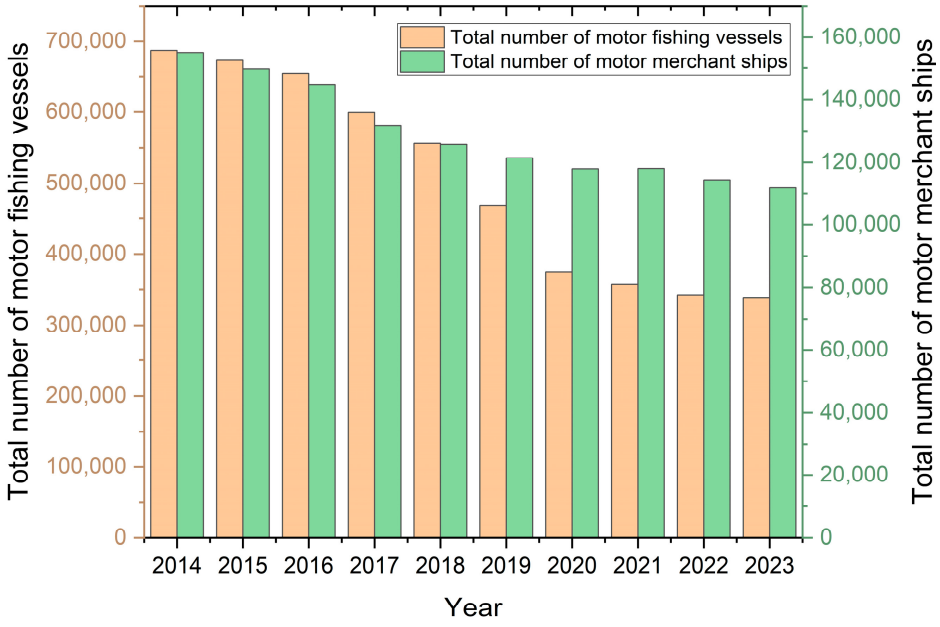


Figure 2. Total number of motor fishing vessels and merchant ships in China from 2014–2023.

In the present study, we propose a risk factor coupling model for collision accidents between merchant ships and fishing vessels based on the N-K model. The aims were to quantify the risk factors of collisions between merchant ships and fishing vessels in China's coastal waters, calculate the coupling values of the main and secondary subfactors under different coupling modes (single-, double-, and multi-factor coupling), and reveal the coupling mechanism of collision between merchant ships and fishing vessels. The findings may provide theoretical support for maritime regulatory agencies in formulating policies and regulations, ensuring maritime safety, and safeguarding the safety of personnel and property. The remainder of this paper is organized as follows. Section 2 is the literature review. Section 3 introduces the data sources and analyses of collision accidents between merchant ships and fishing vessels. Section 4 describes the methods proposed in this study. Section 5 describes the application of the proposed method using a case study and discusses the limitations of the proposed model. Finally, the conclusions are presented in Section 6.

2. Literature Review

Collision accidents between merchant ships and fishing vessels have attracted the attention of governments and scholars worldwide because of their frequent occurrence and serious consequences. The safety of fishing vessels has been a matter of concern for the International Maritime Organization since its inception [11]. Uğurlu et al. [6] found that fishing vessel-related collisions is one of the most common types of maritime accidents. Significant relationships have been described among collision accidents and vessel length, vessel age, loss of life, and loss of vessel. Collision accidents of fishing vessels with other ships has become one of the major hazards faced by marine fishermen [12]. Maritime accidents involving fishing vessels are an important component of marine engineering research because of the high incidence of collisions [13]. Furthermore, because of the numerous fishing vessels navigating close to the coast, collisions between merchant ships and fishing vessels occur frequently, resulting in the sinking of fishing vessels or the loss of life and property [14]. Fishing vessels registered in South Korea accounted for approximately 88% of all vessel registrations, and fishing vessel accidents accounted for approximately 80% of all ship collisions, resulting in multiple casualties between 2010 and 2014 [15]. Collision accidents involving fishing vessels and cargo ships frequently

occur in the waters near Japan, where fishing vessel accidents have claimed the most lives [16]. According to data from the Japan Marine Accident Tribunal, collision accidents accounted for the highest proportion of many maritime accidents in 2019, with fishing vessels contributing the highest proportion (41%) among the vessels involved in collision accidents [17]. According to accident statistics from 2000 to 2020 in Chinese waters, more than 52.7% of maritime accidents were collision accidents, with fishing vessels accounting for a considerable proportion of these accidents [18–20]. Based on accident data from the China Maritime Safety Administration, collision accidents between merchant ships and fishing vessels account for approximately half of all collision accidents [21–23]. The foregoing data highlight the common occurrence of collisions between merchant ships and fishing vessels in maritime transportation.

Understanding why collision accidents occur between merchant ships and fishing vessels occur and how to prevent their recurrence is an essential part of improving maritime traffic safety. Many scholars have also conducted research on the causes of collision accidents between merchant ships and fishing vessels [6,14,24,25]. Uğurlu et al. [6] used Bayesian networks and chi-square tests to analyze fishing vessel accidents that occurred between 2008 and 2018, only considering fishing vessels $\geq$ 7 m in length. Wang et al. [14] proposed a hybrid method that combines human factor analysis and classification systems with Bayesian networks to study the human and organizational factors involved in collision accidents between merchant ships and fishing vessels. Zhang et al. [24] used the human factors analysis and classification system model as a comprehensive framework to extract risk factors leading to collision accidents between merchant ships and fishing vessels in Chinese waters and proposed some collision accident prevention and control strategies. These studies indicate that there are many factors that lead to collision accidents between merchant ships and fishing vessels, including human, management, ship, and environmental factors.

The causes of collision accidents have become more complex over time owing to several factors. The mechanism that triggers collision accidents between merchant ships and fishing vessels is the coupling effect of multiple factors. A single risk factor can affect the navigational safety of ships, and the coupling of multiple risks is more likely to lead to collision accidents. However, few scholars have studied the coupling relationship among the risk factors of collision accidents between merchant ships and fishing vessels, as different risk factors are usually considered independent events, and their coupling effects are ignored. The interdependence between the causal factors of ship collision accidents is becoming increasingly evident [26–28]. Deng et al. [26] used the N-K model to analyze the risk coupling characteristics of maritime accidents in China's inland and coastal waters. Meng et al. [27] proposed a method for quantitatively coupling risk assessment of 304 ship collision accidents from four aspects—human, ship, environment, and management—using the N-K model and Bayesian network analyses. Owing to the relative difficultly in collecting data of collision accidents between merchant ships and fishing vessels, the above research analyses did not pay attention to the collision problem between merchant ships and fishing vessels. Yang et al. [28] analyzed the characteristics and causes of collision accidents between merchant ships and fishing vessels in the coastal areas of Shandong and Zhejiang provinces in China, and provided corresponding preventive measures. However, Yang et al. [28] did not consider the mutual influence between different factors in collision accidents between merchant ships and fishing vessels. Although some scholars [26,27,29] have applied the N-K model to the field of maritime transportation safety and quantified the coupling values between the factors involved, the coupling of risk factors for collision accidents between merchant ships and fishing vessels has not yet been considered. The collision between merchant ships and fishing vessels is one of

the most concerning maritime traffic safety issues in China. Therefore, it is important to conduct research on the coupling effects of causal factors around collision accidents between merchant ships and fishing vessels, clarify the mechanism of collision accidents between merchant ships and fishing vessels from the perspective of the overall system, and implement effective response measures.

3. Accident Statistics

This section includes accident data collection, types of accidents and injuries, types and quantities of vessels involved in the accident, risk factor identification, and risk factor analysis of accident cases.

3.1. Collection of Accident Data

For this study, we selected and analyzed a total of 132 accident investigation reports issued by the China Maritime Safety Administration from 2014 to 2023, which included collision accidents between merchant ships and fishing vessels. The geographical locations of the collision accidents are shown in Figure 3. Notably, the areas prone to collision accidents between merchant ships and fishing vessels are the waters of the west side of Bohai Bay, Ningbo Zhoushan Port, Pearl River Estuary, and near the Qiongzhou Strait. These areas usually have a dense flow of ship traffic, increasing the risk of collisions between merchant ships and fishing vessels.

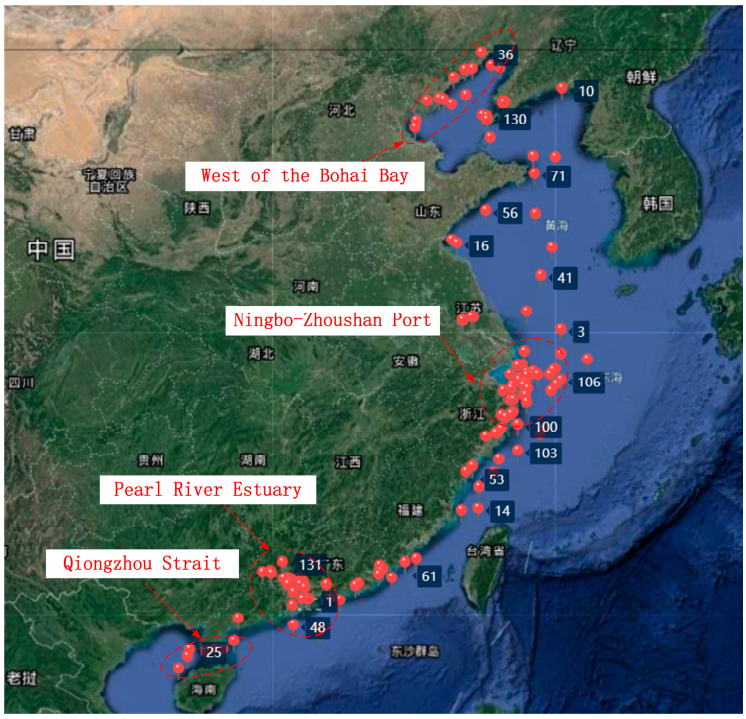


Figure 3. Geographic distribution of collision accidents between merchant ships and fishing vessels within Chinese coastal waters from 2014 to 2023.

Based on the classification regulations for water traffic accidents in China, large-scale accidents and the aforementioned collision accidents are typical accidents that require key prevention measures owing to the many casualties, serious resultant environmental pollution, and huge economic losses. According to the Chinese accident classification standard [18,25], the collision accidents between merchant ships and fishing vessels investigated in this study included 81 general accidents, 41 large accidents, and 10 major accidents (Figure 4).

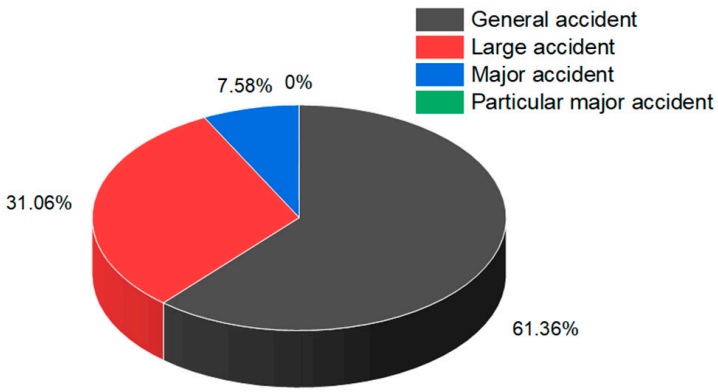


Figure 4. Proportion of collision accidents according to different categories.

3.2. Types of Accidents and Injuries

Based on the accident investigation reports, this study analyzed the relevant content of the accidents. As shown in Figure 5, among the 132 collision accidents between merchant ships and fishing vessels analyzed, 107 resulted in fatalities or missing persons, accounting for 81.1% of the total number of collision accidents. Of the 107, 34 resulted in the death or disappearance of more than five people, accounting for 25.8% of the total. The most serious accident was a collision between a Maltese bulk carrier and a trawl fishing vessel in the waters of Zhoushan, Ningbo, resulting in 14 deaths and five missing persons from the fishing vessel.

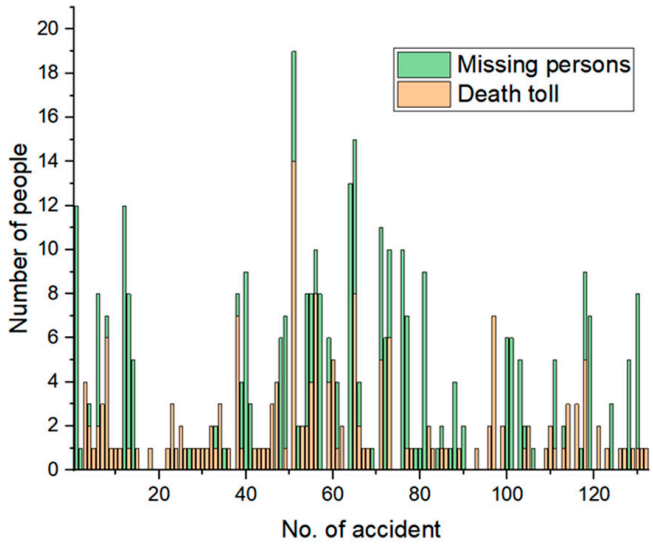


Figure 5. Casualties caused by collision accidents between merchant ships and fishing vessels.

3.3. Types and Quantities of Vessels Involved in Accidents

According to the accident reports, the types of merchant ships involved in collisions with fishing vessels included multi-purpose ships, container ships, dry bulk carriers, cargo ships, oil tankers, and roll-on/roll-off ships. As shown in Figure 6, dry bulk carriers, cargo ships, and container ships ranked among the top three, and were involved in 79 (59.8%), 19 (14.4%), and 15 (11.4%) accidents, respectively. Among the merchant ships that collided with Chinese coastal fishing vessels, general cargo ships and dry bulk carriers accounted for the vast majority, accounting for 74.24% of the total. Different types of ships usually represent different maneuverability and cargo status, and both maneuverability and cargo status are related to the ship factors. The reference [30] also found that dry bulk carrier and general cargo ships in the coastal waters of China have the highest risk of maritime

accidents, with collision accidents accounting for a higher proportion. As shown in Figure 7, the merchant ships involved were registered in 15 countries and regions, including China, Singapore, Malta, Hong Kong, the Philippines, Vietnam, Liberia, Greece, Qatar, Panama, Belize, and the Marshall Islands. The majority of ships were registered in China (72%), followed by Hong Kong (6.1%), Panama (6.1%), and Liberia (4.5%). Among the merchant ships that collided with Chinese coastal fishing vessels, ships from Flags of Convenience countries accounted for 48.65%, except for Chinese vessels. Due to relatively relaxed management and supervision of ships and crew, ships from Flags of Convenience are prone to safety hazards, and the probability of ship collisions is high. The reference [31] also found that the ship flag of registration is closely related to ship collision accidents, and ships from Flags of Convenience account for a large proportion of ship collision accidents. For example, Panama and Libya, as Flags of Convenience, are merchant ships that collide more with fishing vessels. According to statistical data, fishing vessels were constructed of steel, fiberglass, cement, and wood, of which steel and wooden vessels accounted for 61.4% and 33.3%, respectively. Most of the fishing vessels involved were small- and medium-sized vessels; 88 vessels measured < 12 m, accounting for 66.7%, 22 fishing vessels ranged from 12 to 24 m, accounting for 16.7%, and 22 vessels were >24 m, accounting for 16.7%.

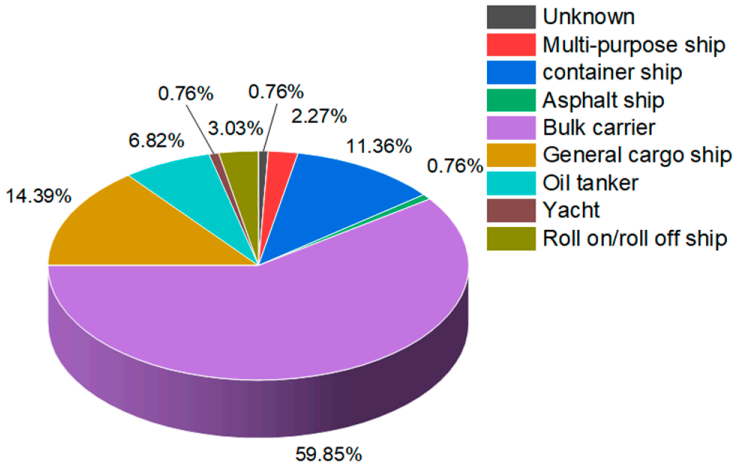


Figure 6. Proportions of merchant ships involved in collision accidents according to the different ship types.

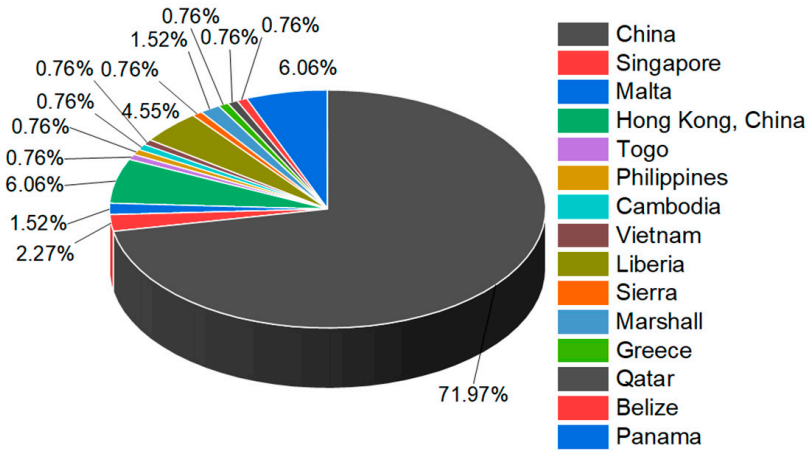


Figure 7. Proportions of merchant ships of different nationalities involved in collision accidents.

3.4. Identification of Risk Factors

Based on the systems engineering theory, the factors influencing maritime safety can be broadly categorized into four groups: human, management, environmental, and ship

factors [18,26,27,32,33]. Each category is amenable to hierarchical decomposition into more specific risk factors.

Human factors are often identified as the primary causes of collision incidents between merchant ships and fishing vessels. They encompass the physical and mental states, theoretical knowledge, practical experience, and communication skills of crew members. A compromised physical or mental state can lead to fatigue, diminished concentration, in turn leading to unsafe behaviors, such as operational errors and lookout negligence. Deficiencies in theoretical knowledge and practical experience can result in decision-making errors and illicit operations. Inadequate communication skills can result in inaccurate information transmission, potentially leading to uncoordinated avoidance maneuvers. Furthermore, some fishermen and ship owners lack safety and legal awareness, necessary safety training, and emergency response capabilities, which pose significant safety threats to fishing vessels operating at sea.

Management factors are often considered the primary reasons for collision incidents involving merchant ships and fishing vessels. These factors encompass both external oversight by maritime and fishery authorities, and the internal management practices of shipping and fishing companies. In China, merchant ships are governed by the Maritime Safety Administration, which falls under the Ministry of Transport, whereas fishing vessels are overseen by fishery administration agencies within the agricultural sector. This fragmented management approach can result in information asymmetry, negatively impacting the effective planning and oversight of water management by regulatory bodies. Ambiguities in responsibility, along with regulatory overlaps or gaps between departments, can increase the risk of collisions. External oversight includes aspects, such as the thoroughness of regulatory frameworks, sufficiency of supervision and management, and standardization of these processes. Internal management involves the robustness of safety management systems for both merchant ships and fishing vessels, as well as the promotion of a safety culture, training, and drills.

Environmental factors play a significant role in the occurrence of collision incidents between merchant ships and fishing vessels. These factors primarily encompass weather and sea conditions, navigable water characteristics, and traffic conditions. Weather and sea conditions refer to the hydro-meteorological elements such as wind, wave height, currents, and visibility within the navigation area. The characteristics of navigable waters pertain to their width and depth, whereas traffic conditions involve the adequacy of navigational aids and facilities and the density of vessel traffic. In regions characterized by intricate navigation environments, high traffic density, and frequent fishing activities, merchant ships and fishing vessels often find themselves in overlapping navigation scenarios. There is a considerable overlap between the established shipping routes of merchant vessels and the traditional fishing grounds. Fishing vessels typically determine their operational zones based on fish population dynamics. During fishing operations, these vessels may not strictly adhere to navigation regulations, and factors such as reduced visibility can significantly increase the risk of collisions in areas where merchant ships and fishing vessels coexist.

Ship factors related to vessels play a crucial role in the occurrence of collision incidents between commercial ships and fishing vessels. These factors encompass various ship parameters, including vessel type, displacement of both merchant ships and fishing vessels, and design of their hulls. In addition, the functionality and condition of maneuvering equipment, navigational aids, communication systems, and other onboard apparatus are significant. Cargo loading conditions on merchant ships and fishing vessels are also sometimes classified as vessel factors. Typically, there are notable disparities in size, speed, and equipment between commercial ships and fishing vessels. Within the merchant ship category, bulk carriers, oil tankers, and container ships exhibit varying speeds. Merchant

vessels generally operate at speeds ranging from 20 to 30 knots, whereas fishing vessels typically do not exceed 20 knots. Furthermore, fishing vessels are characterized by their smaller tonnage, usually tens to hundreds of tons, whereas merchant ships possess considerably larger capacities, with load ranges extending from several hundred to several hundred thousand tons. These differences in tonnage and dimensions complicate their timely detection of each other by merchant ships and fishing vessels. Even minor collisions between these vessels can result in significant damage or capsizing of fishing vessels.

3.5. Risk Factor Analysis of Accident Cases

The collision accident between the "Jinwangling" and "Lurishan Fishing 61027" ships that occurred in the Weihai sea area on 22 December 2022 was analyzed as an example. Three steps were used. The first was text screening, in which report data unrelated to the research in this article was excluded. The excluded data included recommendations for handling personnel and units responsible for the accidents.

The second step was analysis of the cause of the accident. Based on the basic situation of the project, accident process, and handling of the aftermath, in accordance with international collision avoidance rules and navigation practice experience, the direct and indirect causes of the accident were analyzed. This analysis indicated that the direct cause was that the "Jinwangling" and "Lurishan Fishing 61027" ships did not make sufficient judgments on the situation at that time and did not take effective avoidance measures in a timely manner under good visibility weather conditions. The indirect reasons were that the "Lurishan Fishing 61027" vessel was not equipped with sufficient qualified crew members as required by regulations, and the locations of the water area outside the Chengshantou traffic separation system, which is a habitual route of traditional merchant ships and habitual navigation operational area of fishing vessels. The complex traffic flow and dense navigation of commercial and fishing vessels are the indirect causes of accidents.

The third step was to summarize the risk factors for collision accidents. After analyzing the causes of the accident according to the principles of "human, management, environmental, and ship factors", the following accident risk factors of this case were extracted: "failure to make sufficient judgments on the situation at that time and take effective avoidance measures in a timely manner" as a human factor; "failure to equip sufficient competent crew members as required by regulations on the Lurishan Fishing 61027" as a management factor; "the water area is located outside the Chengshantou traffic separation system water area, which is a common commercial ship route and fishing vessel navigation operational area", as a ship factor; and "traffic flow of commercial and fishing vessels is complex and the navigation is dense" as an environmental factor.

A summary of the causes of the 132 collision accidents between merchant ships and fishing vessels revealed that high-frequency causes included negligence in lookout, improper avoidance measures, incorrect assessment of collision risks, complex navigation environments, inadequate ship safety management, and failure to fulfill the obligation of yielding ships. These high-frequency causes, along with other causes, contribute to the occurrence of collision accidents. To effectively eliminate the influence channel between the causes of the aforementioned collision accidents, it is necessary to clarify the relationship between the causes of collision accidents to provide a reference for the prevention of collision accidents between merchant ships and fishing vessels. Based on the above analysis and relevant references, the risk factors of collision accidents between merchant ships and fishing vessels were analyzed, the risk factors in collision accidents between merchant ships and fishing vessels are summarized in Table 1.

Table 1. Risk factors of collision accidents between merchant ships and fishing vessels.

Risk Factors	Specific Risk Points
Human factors	Incompetencies: lack of theoretical knowledge, skill level, and work experience; unfamiliarity with navigation channels; and lack of other abilities. Physical condition: lack of safety awareness, distraction, and mental and physical fatigue. Action errors: improper route maintenance, improper duty, improper ship maneuvering, improper lookout, and failure to take early action. Decision errors: incorrect ship collision hazard assessment, insufficient communication, improper emergency behavior, improper use of instruments and equipment. Violation: failure to comply with maritime collision avoidance rules, failure to use safe sailing speed, illegal fishing, and navigation beyond the specified navigation area.
Management factors	Organizational management: inadequate resource management, lack of positive work environment, improper organizational processes, absence of a robust safety culture, insufficient staffing, and incomplete emergency plans. Safety supervision: inadequate supervision, improper operation plan, incomplete system, and imperfect safety management system.
Environmental factors	Natural environment: visibility, sea conditions such as wind, currents, and waves. Navigation environment: navigational channels, aids to navigation, vessel density, and traffic flow.
Ship factors	Static factors: ship type, ship size, ship age, and mechanical equipment. Dynamic factors: cargo loading status, life-saving equipment, performance of navigation equipment and instrument, and communication systems.

4. Methods

According to the theory of complex systems, the evolution process of collision accidents between merchant ships and fishing vessels is a dynamic risk coupling process of complex systems. The present paper uses key advantages of the N-K model to study the interactions between multiple factors in ship collision accidents, such as its ability to quantify risk coupling, capture complex interdependencies, and analyze nonlinear risk propagation with less data calibration than Bayesian networks or system dynamics [27,28].

The evolution process of collision accidents between merchant ships and fishing vessels is shown in Figure 8 by applying the triggering principle. In the process of propagating risk factors within the system, breaking through the sub defense system and applying coupling filters will generate new pulses. These new pulses will undergo coupled oscillations to increase the risk flow. Coupling oscillations refers to the interactions between different risk factors within a system. When the risk breaks through the comprehensive defense system, a collision accident occurs between a merchant ship and fishing vessel; alternatively, the risk of their occurrence may increase or potentially create new risks, leading to collisions between merchant ships and fishing vessels.

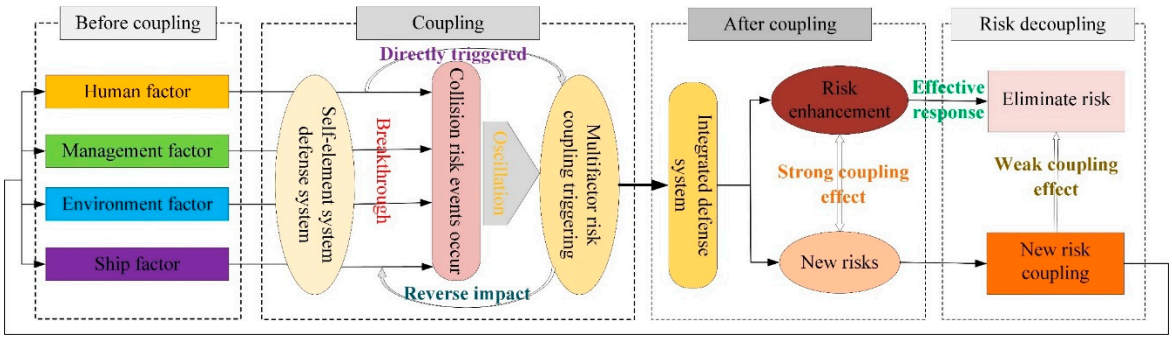


Figure 8. Schematic diagram of the evolutionary mechanism of risk coupling.

According to the number of participating factors, the coupling risk of collision accidents between merchant ships and fishing vessels can be divided into single-, dual-, and multi-factor coupling risks. The corresponding coupling methods are shown in Figure 9.

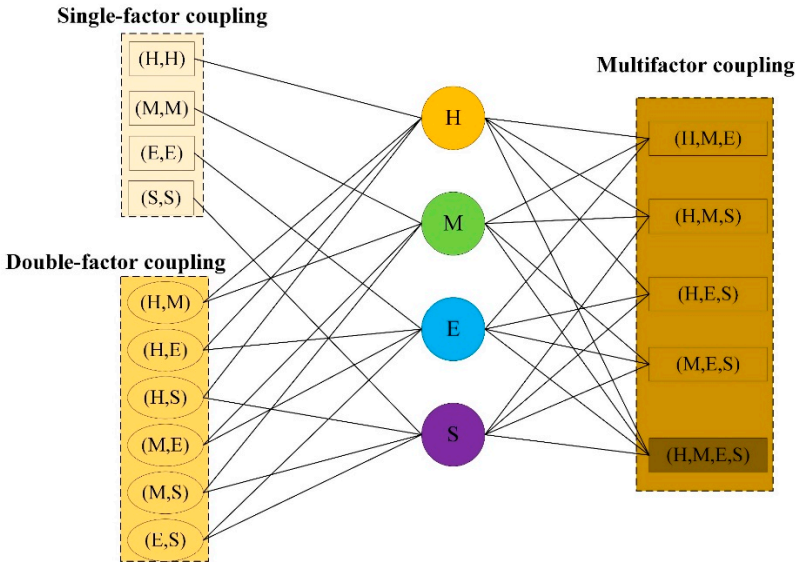


Figure 9. Schematic showing the coupling types of the four risk factors.

The N-K model was employed to construct a risk-coupling measurement model for collision accidents between merchant ships and fishing vessels. Four categories of risk factors, namely human, management, environmental, and ship factors, were considered to calculate the risk-coupling values (T). This quantification aimed to clarify the coupling relationships among different risk factors in such collision accidents. A higher proportion of the coupling method corresponds to a larger risk-coupling T value, thereby increasing the likelihood of collision accidents between merchant ships and fishing vessels.

In the N-K model, N denotes the quantity of system components. Each component can assume n states, resulting in the system having n^N states. K represents the number of interdependent relationships among elements within the system, that is, the number of elements that exert a related impact or influence on a specific element in the system. The minimum value of K is 0, while the maximum value is $N - 1$. When $K = 0$, the state of the system is determined by the characteristics of each individual element that makes up the system. However, if $K > 0$, the state of the system is not only associated with the properties of the constituent elements themselves but also affected by the interactions among these elements. The interaction information T in information theory can be utilized to study the coupling among various elements in complex systems. Here, T reflects the degree of coupling among N elements in the system. In the research on risk coupling in collision accidents between merchant ships and fishing vessels, the formula for computing the interaction information T, taking into account the coupling of human, management, environmental, and ship factors, is as follows:

$$T(H,M,E,S) = \sum_h \sum_m \sum_e \sum_s P(H,M,E,S) \times log_2 \frac{P(H,M,E,S)}{P(H)P(M)P(E)P(S)} \quad (1)$$

4.1. Single-Factor Coupling

Single-factor coupling risk pertains to the risk emerging from the coupling among risk factors within a single category that impacts maritime traffic safety. This encompasses the coupling risks of human, ship, environmental, and management factors. In this study, the corresponding T values are denoted as T_{11} (H), T_{12} (M), T_{13} (E), and T_{14} (S), respectively.

4.2. Dual-Factor Coupling

Dual-factor coupling risk is the risk resulting from the interaction and influence of two risk factors that affect the collision accidents between merchant ships and fishing vessels. It includes the coupling risks between human and management factors, human and environmental factors, human and ship factors, management and environmental factors, management and ship factors, as well as environmental and ship factors. These are represented as T_{21} (H, M), T_{22} (H, E), T_{23} (H, S), T_{24} (M, E), T_{25} (M, S), and T_{26} (E, S), respectively.

$$\begin{cases} T_{21}(H,M) = \sum_h \sum_m P(H,M) \times log_2 \frac{P(H,M)}{P(H)P(M)} \\ T_{22}(H,E) = \sum_h \sum_e P(H,E) \times log_2 \frac{P(H,E)}{P(H)P(E)} \\ T_{23}(H,S) = \sum_h \sum_s P(H,S) \times log_2 \frac{P(H,S)}{P(H)P(S)} \\ T_{24}(M,E) = \sum_m \sum_e P(M,E) \times log_2 \frac{P(M,E)}{P(M)P(E)} \\ T_{25}(M,S) = \sum_m \sum_s P(M,S) \times log_2 \frac{P(M,S)}{P(M)P(S)} \\ T_{26}(E,S) = \sum_e \sum_s P(E,S) \times log_2 \frac{P(E,S)}{P(E)P(S)} \end{cases} \quad (2)$$

where $P(H, M)$, $P(H, E)$, $P(H, S)$, $P(M, E)$, $P(M, S)$ and $P(E, S)$ signify the joint probabilities of two types of risk factors.

4.3. Multi-Factor Coupling

Multi-factor coupling risk refers to the risk generated by the interaction and influence of three or more risk factors that have an impact on the collision accidents between merchant ships and fishing vessels. Multi-factor coupling risks include the coupling risks of the human, management, and environmental factors, human, management, and ship factors, human, environmental, and ship factors, management, environmental, and ship factors, and human, management, environmental, and ship factors. The coupling risk T of the three factors is denoted as T_{31} (H, M, E), T_{32} (H, M, S), T_{33} (H, E, S), and T_{34} (M, E, S). The four factor coupling risk T is denoted as $T41$ (H, M, E, S).

$$\begin{cases} T_{31}(H,M,E) = \sum_h \sum_m \sum_e P(H,M,E) \times log_2 \frac{P(H,M,E)}{P(H)P(M)} \\ T_{32}(H,M,S) = \sum_h \sum_m \sum_s P(H,M,S) \times log_2 \frac{P(H,M,S)}{P(H)P(M)P(S)} \\ T_{33}(H,E,S) = \sum_h \sum_e \sum_s P(H,E,S) \times log_2 \frac{P(H,E,S)}{P(H)P(E)P(S)} \\ T_{34}(M,E,S) = \sum_m \sum_e \sum_s P(M,E,S) \times log_2 \frac{P(M,E,S)}{P(M)P(E)P(S)} \\ T_4(H,M,E,S) = \sum_h \sum_m \sum_e \sum_s P(H,M,E,S) \times log_2 \frac{P(H,M,E,S)}{P(H)P(M)P(E)P(S)} \end{cases} \quad (3)$$

where $P(H, M, E)$, $P(H, M, S)$, $P(H, E, S)$, $P(M, E, S)$, and $P(H, M, E, S)$ are the joint probabilities of multiple types of risk factors.

5. Results and Discussion

5.1. Risk Coupling Frequency Analysis of Collision Accidents

The report data of 132 collision accidents between merchant ships and fishing vessels in Chinese waters were analyzed. In the N-K model, the non-occurring and occurring situations are represented by 0 and 1, respectively, resulting in 16 possible risk coupling situations. By analyzing the statistical data of collision accidents, the number of risks coupling occurrences and the frequency of each coupling occurrence were obtained. The results are summarized in Table 2. The N-K model was used to calculate the probability change in a single-, double-, and multi-risk factors. A value of 1 and 0 indicates that such risks are involved and not involved, respectively.

Table 2. Number of risk couplings and corresponding frequency of collision accidents.

Single-Factor Coupling		Double-Factor Coupling		Multi-Factor Coupling	
Occurrences	**Frequency**	**Occurrences**	**Frequency**	**Occurrences**	**Frequency**
$n_{0000} = 0$	$P_{0000} = 0$	$n_{1100} = 11$	$P_{1100} = 0.08333$	$n_{1110} = 42$	$P_{1110} = 0.31818$
$n_{1000} = 8$	$P_{1000} = 0.06061$	$n_{1010} = 48$	$P_{1010} = 0.36364$	$n_{1101} = 6$	$P_{1101} = 0.04545$
$n_{0100} = 0$	$P_{0100} = 0$	$n_{1001} = 1$	$P_{1001} = 0.00758$	$n_{1011} = 3$	$P_{1011} = 0.02273$
$n_{0010} = 0$	$P_{0010} = 0$	$n_{0110} = 0$	$P_{0110} = 0$	$n_{0111} = 0$	$P_{0111} = 0$
$n_{0001} = 0$	$P_{0001} = 0$	$n_{0101} = 1$	$P_{0101} = 0.00758$	$n_{1111} = 1$	$P_{1111} = 0.09091$
--	--	$n_{0011} = 0$	$P_{0011} = 0$	--	--

Regarding the calculation of the single-risk factor change probability, taking the single-factor change probability of human factors as an example, which includes scenarios involving ship-environmental-management factors and those without, the probability of maritime accidents when all human factors are engaged in their coupling can be computed using Equation (1). The asterisks (*) imply that this factor can be either "1" or "0".

(1) Single-factor risk coupling analysis. For calculating the T value, we initially determined the probability of risk-coupling occurrence in the following distinct manners.

Based on Equation (1), it is essential to calculate the values of $P(H)$, $P(M)$, $P(E)$, and $P(S)$. The probability of accidents occurring when human factors are not involved in risk-coupling is:

$P_{0***} = P_{0000} + P_{0100} + P_{0010} + P_{0001} + P_{0001} + P_{0110} + P_{0101} + P_{0011} + P_{0111} = 0$. Similarly, P_{1***}, P_{*0**}, P_{*1**}, P_{**0*}, P_{**1*}, P_{***0}, and P_{***1}. The calculation results are presented in Table 3.

Table 3. Probabilities of risk coupling events for single factors.

$P_{0***} = 0.00758$	$P_{*0**} = 0.45455$	$P_{**0*} = 0.20455$	$P_{***0} = 0.82576$
$P_{1***} = 0.99242$	$P_{*1**} = 0.54545$	$P_{**1*} = 0.79545$	$P_{***1} = 0.17424$

(2) Dual-factor risk coupling analysis: Using Equation (2), it was necessary to calculate the values of $P(H, M)$, $P(H, E)$, $P(H, S)$, $P(M, E)$, $P(M, S)$, and $P(E, S)$. The probability of accidents occurring when human factors and equipment factors are not involved in risk coupling is $P_{00**} = P_{0000} + P_{0010} + P_{0001} + P_{0011} = 0$, $P_{00**} = 0$. Similarly, other P-values were calculated and are shown in Table 4.

Table 4. Probabilities of risk coupling events for double-factors.

$P_{00**} = 0$	$P_{*00*} = 0.06818$	$P_{0*0*} = 0.00758$	$P_{0**0} = 0$	$P_{*0*0} = 0.42424$	$P_{**00} = 0.14394$
$P_{01**} = 0.00758$	$P_{*10*} = 0.13636$	$P_{0*1*} = 0$	$P_{0**1} = 0.00758$	$P_{*0*1} = 0.03030$	$P_{**01} = 0.06061$
$P_{10**} = 0.45455$	$P_{*01*} = 0.38636$	$P_{1*0*} = 0.19697$	$P_{1**0} = 0.82576$	$P_{*1*0} = 0.40152$	$P_{**10} = 0.68182$
$P_{11**} = 0.53788$	$P_{*11*} = 0.40909$	$P_{1*1*} = 0.79545$	$P_{1**1} = 0.16667$	$P_{*1*1} = 0.14394$	$P_{**11} = 0.11364$

(3) Multi-factor risk coupling analysis. According to Equation (3), it is necessary to calculate the $P(H, M, E)$, $P(H, M, S)$, $P(H, E, S)$, and $P(M, E, S)$ values. The probability of accidents occurring when human, equipment, and environmental factors are not involved in risk coupling was calculated as $P_{000*} = P_{0000} + P_{0001} = 0 + 0 = 0$. Similarly, other P-values were calculated and are listed in Table 5.

Table 5. Probabilities of risk coupling events for multiple factors.

$P_{000*} = 0$	$P_{100*} = 0.06818$	$P_{010*} = 0.00758$	$P_{001*} = 0$	$P_{110*} = 0.12879$	$P_{101*} = 0.38636$
$P_{011*} = 0$	$P_{111*} = 0.40909$	$P_{00*0} = 0$	$P_{10*0} = 0.42424$	$P_{01*0} = 0$	$P_{00*1} = 0$
$P_{11*0} = 0.40152$	$P_{10*1} = 0.03030$	$P_{01*1} = 0.00758$	$P_{11*1} = 0.13636$	$P_{0*00} = 0$	$P_{1*00} = 0.14394$
$P_{0*10} = 0$	$P_{0*01} = 0.00758$	$P_{1*10} = 0.68182$	$P_{1*01} = 0.11364$	$P_{0*11} = 0$	$P_{1*11} = 0.05303$
$P_{*000} = 0.06061$	$P_{*100} = 0.08333$	$P_{*010} = 0.36364$	$P_{*001} = 0.00758$	$P_{*110} = 0.31818$	$P_{*101} = 0.05303$
$P_{*011} = 0.02273$	$P_{*111} = 0.09091$	$P_{0000} = 0$	$P_{1000} = 0$	$P_{0100} = 0$	$P_{0010} = 0$
$P_{0001} = 0$	$P_{1100} = 0.08333$	$P_{1010} = 0.36364$	$P_{1001} = 0.00758$	$P_{0110} = 0$	$P_{0101} = 0.00758$
$P_{0011} = 0$	$P_{1110} = 0.31818$	$P_{1101} = 0.04545$	$P_{1011} = 0.02273$	$P_{0111} = 0$	$P_{1111} = 0.09091$

5.2. Risk Coupling Result and Analysis

Based on Equations (2) and (3), the coupling degree values were calculated, as shown in Table 6. For double-factors risk coupling, the coupling degree values were as follows: $T_{21} = 0.0067$, $T_{22} = 0.0175$, $T_{23} = 0.0193$, $T_{24} = 0.0112$, $T_{25} = 0.0526$, and $T_{26} = 0.0174$. For multi-factors risk coupling, the coupling degree values were as follows: $T_{31} = 0.0333$, $T_{32} = 0.0740$, $T_{33} = 0.0487$, $T_{34} = 0.0739$, and $T_4 = 0.1083$. Therefore, the coupling degrees values were ranked as follows: $T_4 > T_{32} > T_{34} > T_{25} > T_{33} > T_{31} > T_{23} > T_{22} > T_{26} > T_{24} > T_{21}$, as shown in Table 6 and Figure 10.

Table 6. Risk coupling results and ranking.

No.	Results of Risk Coupling	Rank
1	$T_4(H, M, E, S) = 0.1083$	1
2	$T_{31}(H, M, E) = 0.0333$	6
3	$T_{32}(H, M, S) = 0.0740$	2
4	$T_{33}(H, E, S) = 0.0487$	5
5	$T_{34}(M, E, S) = 0.0739$	3
6	$T_{21}(H, M) = 0.0067$	11
7	$T_{22}(H, E) = 0.0175$	8
8	$T_{23}(H, S) = 0.0193$	7
9	$T_{24}(M, E) = 0.0112$	10
10	$T_{25}(M, S) = 0.0526$	4
11	$T_{26}(E, S) = 0.0174$	9

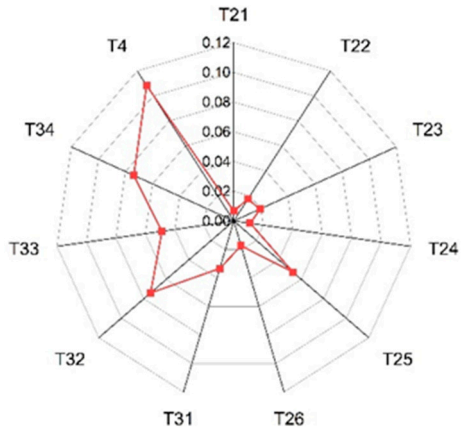


Figure 10. Risk coupling results.

Based on the measurement of the risk coupling effects and the combination of coupling interaction types, the analysis of the coupling results for each factor is as follows:

(1) Overall, the coupling value of risk factors for collision accidents between merchant ships and fishing vessels is generally positively correlated with the number of coupling risk factors involved; that is, when the human, ship, environmental, and management factors in the water transportation system are coupled, the risk value is the highest. Although the calculation results show that the risk of coupling management and ship factors is greater than that of coupling human, ship, and environmental factors and management, environmental, and ship factors, the overall trend is that the risk of coupling three factors is greater than that of coupling two factors.

(2) In the four cases where three factors are coupled, when the risk coupling value is high, it includes the ship factor. In contrast, the coupling value of the three factors that do not include the ship factor is smaller than the coupling value of the human and management factors. Ship factors play a crucial role in the traffic safety systems between merchant ships and fishing vessels. When ship factors encounter problems and are coupled with other factors, there is a high probability of collision accidents between merchant ships and fishing vessels.

(3) Among the six cases of dual-factor coupling, the risk value of management and ship coupling was the highest, followed by humans and ships, humans and environmental, environmental and ships, management and environmental, and humans and management. The findings indicate that management and ship factors have a significant impact in terms of dual-factor coupling, and the role of the environment in dual-factor coupling must be seriously considered.

In addition, although the coupling risks between humans and management and environmental factors are relatively small, human operational errors, improper fishing vessel supervision measures, and harsh navigation environments are usually the direct factors that cause collisions between merchant ships and fishing vessels and should also be seriously considered.

Compared with the other two factors, changes in ship and environmental factors have a greater impact on the possibility of coupling. Therefore, improvements in ship and environmental factors can bring significant changes to the possibility of coupling. However, considering that environmental factors are often difficult to change, prioritizing measures that include strengthening the maintenance of fishing vessels and merchant ships, ensuring good performance of ship equipment, loading ship cargo in compliance with regulations, and ensuring that ships are equipped with sufficient life-saving equipment has become a more practical and effective approach.

The present paper analyzes the collision accident cases between Chinese coastal merchant ships and fishing vessels, and uses the N-K model to analyze the coupling relationship between different influencing factors of human–management–environment–ship, which has certain guiding significance for preventing similar accidents from occurring. The present paper only analyzed the coupling relationship of four influencing factors, and further analysis of the causal relationship of accidents requires the use of Bayesian networks or complex network models. The data of 132 collision accidents between merchant ships and fishing vessels studied in the present paper is limited to the coastal waters of China from 2013 to 2023, and its research scope has certain limitations. Due to the lack of essential monitoring equipment on many fishing vessels, it is impossible to monitor and monitor all fishing activities in the jurisdictional area. Therefore, accident analysis can only be conducted through records related to merchant ships and passing vessels after an accident occurs, which to some extent may affect the objectivity of the results. In addition, the data selected in the present paper are official data released by the China Maritime Safety Administration and do not include data on collision accidents between merchant ships and fishing vessels that are not officially counted or published. Therefore, in terms of

applicability to other regions, the results of this study have certain limitations and may have certain biases. There are differences in the activity patterns and regulatory completeness of fishing vessels in different countries or regions, and the research results may vary. Further research and verification are still needed for situations in other countries or regions.

5.3. Suggestions for Preventing Collisions Between Merchant Ships and Fishing Vessels

The frequent collisions between commercial and fishing vessels in coastal waters is an important issue for the Chinese government. In 2021, the State Council Work Safety Committee issued the "Opinions on Strengthening the Risk Prevention and Control of Water Transport and Fishery Ship Safety." Subsequently, the Ministry of Transport and the Ministry of Agriculture and Rural Affairs jointly launched the "Commercial and Fishery Co-governance" special action in accordance with the relevant requirements. To date, the special action of commercial and fishery co-governance has been conducted for three consecutive years (2021–2023). This special work continues to promote the resolution of prominent issues, such as the cross-navigation of commercial fishing vessels, crew negligence in lookouts, and insufficient safety awareness. The joint rectification has achieved preliminary results. According to the latest statistical data, in 2023, the number of general and more serious collision accidents between merchant ships and fishing vessels and the number of deaths and missing persons along the coast of China decreased by 31.2% and 28.9%, respectively, compared to 2022. Collision accidents between merchant ships and fishing vessels still occur frequently. For example, on the afternoon of 21 October 2024, a cargo ship collided with a fishing vessel in the waters of Ningde, Fujian, China. Four people on board the fishing vessel went missing. To effectively control and reduce the coupling of maritime traffic safety risks, four suggestions are proposed.

The first suggestion concerns human factors, specifically, deepening the promotion of educational work and comprehensively improving the practitioners' quality. Management departments should strengthen professional knowledge training for the fishing vessel crews, including understanding merchant ships navigation habits and fishing vessels activities, familiarizing themselves with the distribution of navigation elements, signal lights and shapes; paying attention to practical training and emergency drills; identifying problems during practical operations; strengthening pre-management and arranging emergency rescue work in advance; effectively understanding and eliminating the misunderstandings between merchant ship and fishing vessel crews and fully utilizing new media and new forms; expanding the audience's scope of publicity, education, and training; and promoting mutual understanding and communication between both parties.

The second suggestion concerns ship maintenance and inspection related to ship factors. Fishing vessels should be equipped with new identification and positioning communication devices, and all fishing vessels operating on the merchant ships routes must be equipped with AIS responders. The safety performance of ships must be regularly inspected and detailed checks and tests on communication and navigation equipment must be performed to reduce the possibility of safety risks caused by equipment failures. Furthermore, a shared platform for ship information and environmental information should be established. This would facilitate the real-time exchange of navigation information and dynamics between merchant ships and fishing vessels, including but not limited to the vessel's location, speed, heading, estimated arrival time, emergency contact information, as well as environmental information, such as weather and hydrology in the water area, and relevant navigation warning information. Before setting sail, merchant ships and fishing vessels must upload their navigation plans to the shared platform in advance, especially in the areas where the waterways intersect, to inform and clarify their respective navigation

intentions in advance, and to make corresponding navigation adjustments in a timely manner to reduce collision risks.

The third suggestion is to strengthen maritime supervision and regulatory development in terms of management factors. The Maritime Safety Administration, Navigation Control Department, and Fishery Administration and Fishing Port Supervision and Management Department should enhance coordination and linkage, and jointly carry out joint maritime law enforcement actions. A sound collaborative consultation mechanism should be established, communication and connection between fishing vessels and merchant ship supervision departments should be strengthened, a notification and rescue linkage mechanism should be established, and joint patrols and inspections between the two departments performed. Carry out targeted law enforcement patrols and real-time monitoring of high-risk areas, and implement dynamic restricted zones during peak fishing periods. Clear penalties and stricter enforcement will be imposed on violations committed by merchant ships and fishing vessels. In addition, safety warning training must be actively carried out, pre-management safety warning mechanisms and post-management accident handling systems must be established, and water transportation safety must be further improved.

The fourth suggestion concerns environmental factors. The government should coordinate the planning of marine resource utilization and jointly create a suitable water transportation environment. Based on regional characteristics, the reasonable and scientific planning of water area functions should be conducted, and moderate transfers and revisions should be made to high-risk areas where existing agricultural and fishery operation areas overlap with recommended routes. These actions would reduce the probability of intersection and collision between commercial and fishing vessels, effectively resolve port, commercial, and fishery conflicts, and fundamentally improve the safety of ship navigation, berthing, and operations.

More importantly, the critical and effective measure is the control of key factors. The calculation results of risk values based on different coupling forms between risk factors of collision accidents between merchant ships and fishing vessels show that the coupling between management factors and ship factors (T_{23}) is 0.0526, which is the maximum value of dual-factor coupling and has a significant impact on collision accidents between merchant ships and fishing vessels. When there are issues with ship factors and regulatory oversight, collision accidents are prone to occur. On the one hand, considering the factors of ships, strict supervision should be carried out when there are defects or other problems with ships to avoid collision accidents. According to existing accident data, many collisions between merchant ships and fishing vessels have occurred due to the lack of navigation aids and poor conditions or unseaworthiness of fishing vessels. Therefore, it is necessary to improve the maintenance and upkeep of fishing vessels, enhance the level of ship safety management, and reduce their impact on risks. On the other hand, considering management factors, collisions between merchant ships and fishing vessels often occur during the fishing season, and fishing vessels still habitually violate collision avoidance rules or illegally occupy waterways for fishing. Therefore, it is necessary to strengthen and improve the maritime traffic management and supervision system, target enforcement patrols and real-time monitoring of high-risk zones, and clear penalties and stricter enforcement for violations. Especially during the fishing season, dynamic restriction zones in areas with frequent fishing activities must be implemented, clear rules and guidance should be provided for the safe navigation of merchant ships and fishing vessels, patrols and supervision should be strengthened in key areas and important time periods, and effective collision prevention measures should be taken for shipping and fisheries.

Moreover, according to the analysis of the multi-factor risk coupling, except the four factors coupling (T_4), the maximum coupling value of human factors, management factors,

and ship factors (T_{32}) is 0.074, which also contributes significantly to the occurrence of collision accidents. Among the 132 accidents, many collisions between commercial and fishing vessels were caused by human error, lax supervision, and defects in the fishing vessels. Therefore, in the actual process of preventing collision accidents between merchant ships and fishing vessels, in addition to ensuring the good performance of merchant ships and fishing vessels, improving management systems, and effectively fulfilling regulatory work, education of professional skills and the safety awareness of the fishing vessels' crews are also key measures to reduce the occurrence of collision accidents.

To sum up, to prevent collisions between merchant ships and fishing vessels, we cannot begin with single-factor prevention. More attention should be paid to the coupling between different risk factors and measures should be taken to eliminate these risk factors, which is the key to reducing accidents. One measure is to avoid coupling of multiple risk factors. Many risk factors affect maritime traffic safety. When one factor presents a risk, there is a high probability of other risk factors having risks as well. Therefore, it is necessary to eliminate known hazards as early as possible, while performing a com-prehensive investigation of other risk factors to prevent coupling effects between factors.

6. Conclusions

A collision between merchant ships and fishing vessels represents a complex incident, intertwined with numerous associated risks. Collision accidents cannot be ascribed to a single one among the four factors—human, ship, environmental, and management. Instead, they result from the intricate interaction of these diverse risk elements. Thus, the concept of risk coupling holds substantial significance in the analysis of risk-factor interactions within merchant–ship–fishing–vessel collision accidents. In this research, the characteristics of these collisions were explored through the analysis and extraction of 132 historical collision incidents that occurred in Chinese coastal waters between 2013 and 2023. The N-K model was utilized to construct a risk model for these collisions, enabling the analysis of the coupling effects among different risk factors. The finding supports three conclusions:

Firstly, the risk of collision accidents between merchant ships and fishing vessels escalates progressively with the increase in risk-coupling factors. Notably, the coupling value of all four factors was the highest (0.1083), which was 1.5 times that of the maximum coupling value of three factors and 2.1 times that of the maximum coupling value of two factors. Among the four categories of factors, the risk coupling between ship and environmental factors poses a relatively high probability of accidents. Secondly, to mitigate collision accidents, greater focus should be directed towards the condition of the ships, the state of fishing vessels, the complex and variable meteorological environment, and the water areas where merchant shipping routes intersect with fishing activities. Finally, relevant suggestions and countermeasures can be formulated for human, management, environmental, and ship factors, as well as their coupling scenarios. These findings could potentially contribute to the reduction in collision accidents between merchant ships and fishing vessels.

The present study included only collision accidents between Chinese coastal merchant ships and fishing vessels. Future studies that combine the collision accident data of merchant ships and fishing vessels from other countries globally will reveal more results in the waters of other countries. Furthermore, the present study only analyzed the coupling relationship between influencing factors on the impact of collision accidents between merchant ships and fishing vessels through the N-K model. However, the N-K model is typically based on static environments and fixed rules, while real-world maritime traffic systems may be dynamically changing and often adjusted appropriately. Therefore, studies utilizing Bayesian or complex networks will be valuable in analyzing the impact of important factors in more detail.

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