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Risk Evaluation of Navigation Environment Based on Dynamic Weight Model and Its Application

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Abstract: In order to scientifically and reasonably evaluate the safety risk of ship navigation, to and better solve the problems of the poor sensitivity of static evaluation and insufficient ability to grasp the overall dynamic situation, in this paper, representative safety evaluation indexes for ship navigation are screened and the initial weight of each index is confirmed in combination with the improved analytic hierarchy process (IAHP), in order to learn the changes of navigation environment and accident samples in the waters in the jurisdiction. Finally, the dynamic risk evaluation is carried out by constructing a dynamic weight evaluation model for the safety risk of the navigation environment based on the weight fusion of subjective and objective impact factors. The waters under the jurisdiction of Sanya, China were selected for the study, and the navigation risk of the waters in the jurisdiction was calculated by using the dynamic weight evaluation model based on navigation risk. The calculation results are highly consistent with the results based on the statistics of historical accidents and the analysis of the characteristics of the navigation environment in the jurisdiction. The navigation risk in this water area is the greatest from May to September every year. The dynamic weight evaluation model can not only overcome the subjective evaluation distortion in the traditional risk evaluation theory of navigation environment in practical applications, but can also provide a scientific theoretical basis for the dynamic evaluation and early warning of the risk of ship navigation environments through continuous sample learning.

Keywords: navigation environment risk; dynamic weight; weight fusion; risk evaluation

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1. Introduction

As an important mode of transportation, waterway transportation not only carries more than 90% of the cargo in global international trade, but also is a common means of passenger and tourist transport [1]. However, due to the complex environment of waterway navigation, which is significantly affected by variability factors such as wind, waves and flow, the dangerous situations and traffic accidents occur from time to time. How to ensure shipping safety and improve risk prediction and early warning for shipping has become the core problem in the safety study field of waterway transportation.

Due to its relatively late start, modern maritime studies not only lag behind in the theoretical research on waterway safety and risk, but also still have a certain gap in the study results of road and railway transportation. The traditional safety evaluation methods for ship navigation are mostly static evaluation methods based on the development of safety management theory. On the one hand, they mostly focus on solving the overall risk evaluation problem of large-scale static waters in a jurisdiction [2], which is difficult to apply to the medium- and small-scale maritime safety management process with dynamic changes. On the other hand, the static evaluation method cannot quantitatively define the change process of dynamic risk among the risk factors and the coupling relationship in the change process, thus resulting in the inability to accurately and effectively predict the development trajectory and consequences of the impact factors, and making the risk guarantee measures lack of pertinence. Therefore, how to update and improve the existing evaluation methods for navigation safety and improve the applicability and accuracy of the evaluation methods has become an urgent problem to be solved in the process of improving China's waterway traffic management and realizing the goal of modern maritime management.

The existing studies often adopt one risk evaluation method, such as the probability-based study of ship collision and approach [3–5]. Through statistics of ship collision accidents that have occurred within the jurisdiction, the risk of waters in the jurisdiction is evaluated macroscopically. The visual-based ship encountering risk evaluation method [6], analytic hierarchy process [7], TOPSIS [8], entropy method [9], grey relation analysis [10], deep learning [11] and others may lead to great differences in the results of the safety evaluation of the same waters due to different methods.

In order to overcome the distortion of the evaluation results caused by the traditional static safety risk evaluation of ship navigation, more and more scholars are beginning to try to use the dynamic evaluation method to analyze the safety risk of ship navigation [12]. Some scholars have used the dynamic BN [13] to quantitatively analyze the navigation risk in the Arctic waters and plan the route of ships sailing in the Arctic, so as to achieve the goal of safe navigation. Zhang et al. used accident statistics, expert judgment and fault tree analysis (FTA) to conduct qualitative analysis of ship collision risk [14], the essence of which is still the derivative result after optimizing the static risk. Frontier problems such as the spatial–temporal correlation of risk factors and the dynamic characterization of accident risk have not been fully considered in the risk evaluation

Considering that the occurrence of maritime accidents itself is a small probability event [15], the data samples cannot fully reflect the operation mechanisms and laws of maritime accidents. Hence, in order to avoid the fuzziness and difference of static evaluation and the sensitivity of dynamic evaluation data, and to better combine the advantages of subjective and objective evaluations and make the evaluation results more accurate at the present stage, a navigation safety risk evaluation model based on the weight fusion of subjective and objective impact factors is proposed in this paper, in order to improve the accuracy of ship navigation safety evaluation by combining subjective expert experience and objective accident samples. According to the characteristics of the navigation environment in the waters in the jurisdiction, the representative safety evaluation indexes for ship navigation are selected and the initial weight of each index is confirmed by using the improved analytic hierarchy process (IAHP). Based on the statistical data of accident cases, the changes of the navigation environment in the waters in the jurisdiction and the sample of accident cases are studied. Finally, the dynamic weight evaluation model of navigation environment impact factors is established. The study results in this paper not only enable maritime managerial staff to have a more comprehensive and intuitive understanding of the navigation environment risks based on the current safety situation of the waters, but also objectively improve regional navigation safety level and ship navigation efficiency. Meanwhile, the results can provide a reference for maritime authorities to a certain extent.

2. Construction of Dynamic Weight Evaluation Model of Navigation Environmental Risk

2.1. Construction Process of Dynamic Weight Evaluation Model

The dynamic weight evaluation is based on the identification of risk factors. The spatial–temporal chain change of the factor weight is analyzed, and then the weight degree of the system under different spatial-temporal conditions is calculated by comparing with the established criteria, so as to formulate the countermeasures in a timely and effective manner, which is related to navigation safety.

The construction process of the dynamic weight evaluation model is shown in Figure 1, which mainly includes a series of modeling processes such as determination of original weight, adjustment of subjective and objective weights, fusion of dynamic weights, and so on.

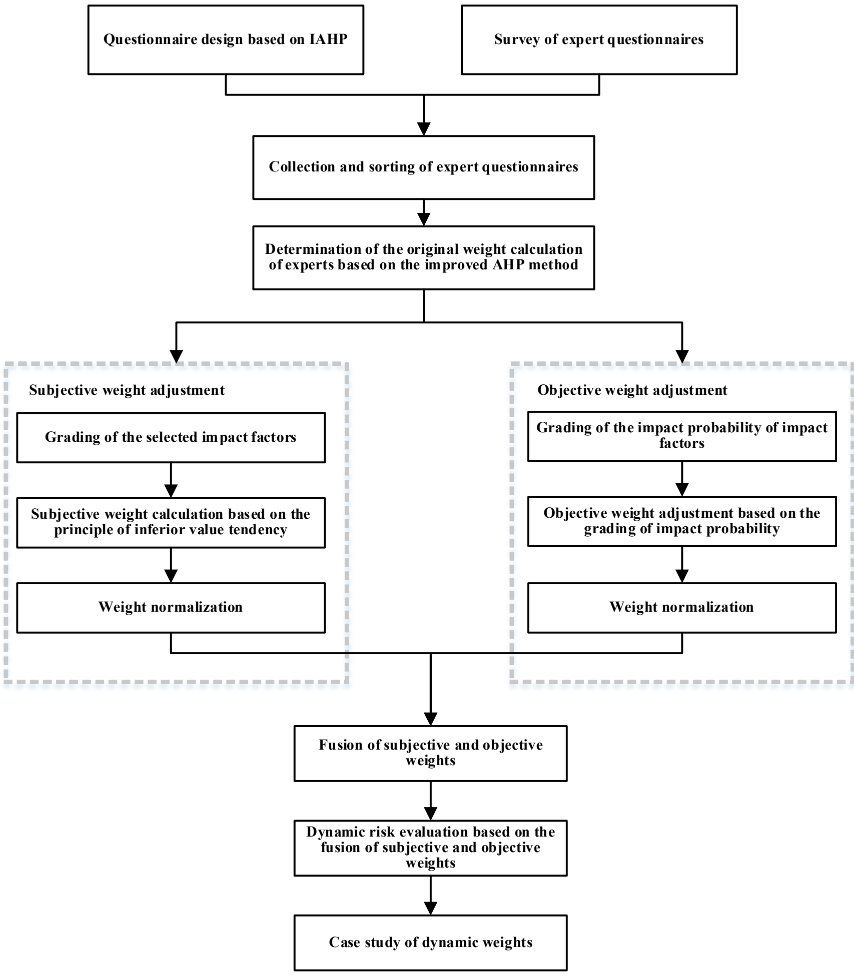

Figure 1. Construction process of dynamic weight risk evaluation model.

2.2. Screening of Impact Factors

Navigation environment [16] refers to the umbrella term of various factors affecting the normal ship navigation and seaway transit capacity as well as the ship's safe navigation, which are difficult to directly control for the maritime department. From a systematic point of view [17], water transportation is a complex system. The impact of any adverse environmental factors on the ship's safe navigation is first reflected in the navigation environment, but its impact degree is predictable. According to the characteristics of the navigation environment in the waters in the jurisdiction, the following environmental factors of navigation were selected for study, as shown in Table 1.

2.3. Determination of Original Weight

In this paper, the analytic hierarchy process (AHP) is adopted to determine the weight value of secondary indicators of ship collision accidents. AHP, which was first proposed by Saaty [18], is a method that can transform the qualitative judgment of complex factors into a quantitative calculation of the weight value of various factors. AHP can help people effectively make decisions and judge the main impact factors of various complex problems.

Table 1. Selection of the impact factors of navigation environment.

	Impact Factors of Navigation Environment	Surveying and Mapping Method
Sea condition environmental factors	Wind Flow Visibility	Calculate with the daily average according to the official measurement data
Factors of seaway conditions	Channel width Channel length Channel curvature Channel crossing Channel obstruction	Count all the seaway data in the jurisdiction
Traffic environment factors	Ship traffic flow	Create statistics according to AIS data
	Ship density	$I = \frac{Q}{vW}$ I is traffic flow density; Q is traffic flow; v is the average velocity of traffic flow; W is traffic flow width.
	Facilities to assist navigation	Consult the local maritime department

Based on the 0.1–0.9 scale process, a triangular fuzzy number is introduced to improve the analytic hierarchy process (AHP), which is most commonly used to determine the original weight. It is proposed that the judgment of importance process via pairwise comparison in the original AHP be simplified to a scale between 0–1 for measurement, and the upper and lower limits are constructed with the scale as the center, so that there is a fuzzy evaluation interval between the pairwise comparison indexes. This way, the situation of too much difference from the actual expression can be avoided, and the accuracy of calculation improved. The meaning of the scale between the IAHP indexes that is proposed in the paper is shown in Table 2.

Table 2. Meaning of scale between the improved AHP indexes.

Scale	Meaning	Scale	Meaning
0.1	The latter is of extreme importance	0.6	The former is of slight importance
0.2	The latter is of much importance	0.7	The former is of obvious importance
0.3	The latter is of obvious importance	0.8	The former is of much importance
0.4	The latter is of slight importance	0.9	The former is of extreme importance
0.5	Both are of equal importance		

2.4. Dynamic Weight Adjustment

2.4.1. Subjective Weight Adjustment

Subjective weighting is a method of giving weight through comprehensive comparison of various indexes with reference to the cognition and experience of evaluators. Assuming that there are n series of the impact factors of the navigation environment based on the data characteristics of maritime accident samples, $E_i(i = 1, 2, 3, \cdots, n)$, if any E_i is discretized into m levels according to the different levels when the impact factors of navigation environment occur, the sequence of the impact factors of the navigation environment can be changed to:

$$E_{ik} \cdot (i = 1, 2, 3, \ldots, n;\ k = 1, 2, 3, \ldots, m,\ m \in N) \tag{1}$$

For any E_i, if E_{ik} transitions from the optimal value to the worst value as k increases from 1 to m, then:

$$SDS_{\min} = SDS(E_{i1}) = 0, SDS_{\max} = SDS(E_{im}) = 1 \tag{2}$$

$$SDS(E_{1k}) = SDS(E_{2k}) = \cdots SDS(E_{nk}) \tag{3}$$

Therefore, when the level of impact factors of ship maritime accidents is the same, it will cause a similar subjective sense of danger. When the level of impact factors is different, it will cause a different subjective sense of danger. For the impact factor sequence of the navigation environment E_{ik}, if the impact factor is at the t-th level after discretization E_i, it is recorded as:

$$t_i = N(E_i) \cdot (i = 1, 2, 3, \ldots, m),\ t_i \in [1, m], t_i \in N \tag{4}$$

$N(E_i)$ is the level in the accident sample.

Then, the subjective weight adjustment coefficient of the impact factors of different navigation environment is C_i calculated as follows:

$$C_i = \frac{t_i}{\sum\limits_{i=1}^{n} t_i} \cdot (i = 1, 2, 3, \ldots, n;\ t_i \in [1, m]) \tag{5}$$

At this time, the subjective weight value based on the level of the impact factors of the navigation environment can be adjusted by the following formula:

$$W_i = \{C_i\} \cdot (i = 1, 2, 3, \ldots, n) \tag{6}$$

After normalization of W_i, the final assignment of the subjective weight adjustment can be obtained.

2.4.2. Objective Weight Adjustment

Objective weighting, mainly based on data collection, is a method of giving specific weight by calculating the contribution degree of each index through the relationship between indicators using mathematical statistical tools. The discrete impact factors of navigation environment risk are defined as B_i, if its probability meets:

$$\pi(B_i) = P(A|B_i) \cdot (i = 1, 2, 3, \ldots n) \tag{7}$$

Then, $\{\pi(B_i),\ (i = 1, 2, 3, \ldots, n)\}$ is the prior impact probability of ship maritime accident risk when the environmental impact factor exists, that is, the causal probability of the impact factor [19,20]. Based on the data on historical ship accidents, the Bayesian method is used in this paper to compare the prior impact probabilities $\pi(B_i)$, which are objectively expressed by different impact factors of navigation environment. The prior impact probabilities $\pi(B_i)$ are divided into m levels. The hierarchy of impact probability is shown in Table 3 below.

Table 3. Hierarchy of impact probability.

Grade	Grading of Impact Probability
1	$\pi(B_i)_{\min} \rightarrow \pi(B_i)_{\min} + \frac{\pi(B_i)_{\max} - \pi(B_i)_{\min}}{m}$
2	$\pi(B_i)_{\min} + \frac{\pi(B_i)_{\max} - \pi(B_i)_{\min}}{m} \rightarrow \pi(B_i)_{\min} + \frac{2(\pi(B_i)_{\max} - \pi(B_i)_{\min})}{m}$
3	$\pi(B_i)_{\min} + \frac{2(\pi(B_i)_{\max} - \pi(B_i)_{\min})}{m} \rightarrow \pi(B_i)_{\min} + \frac{3(\pi(B_i)_{\max} - \pi(B_i)_{\min})}{m}$
4	$\pi(B_i)_{\min} + \frac{3(\pi(B_i)_{\max} - \pi(B_i)_{\min})}{m} \rightarrow \pi(B_i)_{\min} + \frac{4(\pi(B_i)_{\max} - \pi(B_i)_{\min})}{m}$
(k)	$\pi(B_i)_{\min} + \frac{(k-1)(\pi(B_i)_{\max} - \pi(B_i)_{\min})}{m} \rightarrow \pi(B_i)_{\min} + \frac{k(\pi(B_i)_{\max} - \pi(B_i)_{\min})}{m}$
m	$\pi(B_i)_{\min} + \frac{(m-1)(\pi(B_i)_{\max} - \pi(B_i)_{\min})}{m} \rightarrow \pi(B_i)_{\max}$

The maximum value of impact probability is $\pi(B_i)_{\max}$, while its minimum value is $\pi(B_i)_{\min}$. These are divided into m levels

If $\pi(B_i)$ is dispersed into l levels according to different levels when the impact factors of the navigation environment occur, the prior impact probability of the environmental factor risk of navigation is changed to:

$$\pi(B_{ik}) = P(A|B_{ik})\,(i = 1, 2, 3, \ldots, n;\; k = 1, 2, 3, \ldots, l, l \in N) \tag{8}$$

If an impact factor B_i is located in the t-th level of the subjective sense of danger of the impact factor, the impact probability is $\pi(B_i)$ after calculation. When the impact probability is graded according to Table 3, $\pi(B_i)$ is located in the s-th level and recorded as:

$$s_i = N(B_i)(i = 1, 2, 3, \ldots, m); t_i \in [1, m], t_i \in N \tag{9}$$

$N(B_i)$ is the impact probability level of the impact factor B_i.

Then, the objective weight adjustment coefficient P_i, based on accident characteristics, is calculated as follows:

$$P_i = \frac{s_i}{\sum\limits_{i=1}^{n} s_i}(i = 1, 2, 3, \ldots, n) \tag{10}$$

At this time, the objective weight value based on the impact factor level of the navigation environment can be adjusted by the following formula:

$$W_i = \{P_i\}(\; i = 1, 2, 3, \ldots, n) \tag{11}$$

2.5. Dynamic Weight Fusion

In the actual weight fusion, the credibility of the fusion conclusion obtained with a single simple method is questionable. In the paper, the subjective and objective weights based on the initial weight are fused to obtain the finally-fused weight by using grey relation analysis (GRA) in combination with the improved D–S evidence theory. If the initial weight is defined as $X_0 = \{X_{11}, \ldots, X_{1\mathrm{n}}\}$, the subjective weight is $X_\mathrm{s} = \{X_{21}, \ldots, X_{2\mathrm{n}}\}$ and the objective weight is $X_\mathrm{oB} = \{X_{31}, \ldots, X_{3\mathrm{n}}\}$, the following weight matrix can be constructed:

$$X = \begin{vmatrix} X_{11} & X_{12} & \cdots & X_{1\mathrm{n}} \\ X_{21} & X_{22} & \cdots & X_{2\mathrm{n}} \\ X_{31} & X_{32} & \cdots & X_{3\mathrm{n}} \end{vmatrix} \tag{12}$$

The reference vector is obtained by selecting a maximum value from each column of X as the reference weight value:

$$X^* = \{X_1^*, X_2^* \ldots, X_\mathrm{n}^*\} \tag{13}$$

The distance between the initial weight vector X_0, subjective weight vector X_s, objective weight vector X_oB and reference vector X_s is found:

$$D_i^* = \sqrt{\sum\nolimits_{k=1}^{n} \left(x_i^* - x_{ki}\right)^2}(i = 1, 2 \cdots n) \tag{14}$$

After determining the fused weight of initial weight vector X_0, subjective weight vector Xs and objective weight vector X_oB, the selected preference value is the maximum weight value. Therefore, the fused weight is distributed with the furthest from maximum value of the distance as the minimum value of the weight, but the nearest to maximum value of the distance as the maximum value of the weight. Then, they are normalized to obtain the comprehensive weight ω'_m after dynamic fusion, as shown in the following formula:

$$\omega_i = \frac{1}{1 + D_i^*}(i = 1, 2 \cdots n) \tag{15}$$

$$\omega'_m = \left\{ \frac{x_1^* \omega'_1}{\sum_{i=1}^{n} x_i^* \omega'_i}, \frac{x_2^* \omega'_2}{\sum_{i=1}^{n} x_i^* \omega'_i}, \cdots, \frac{x_n^* \omega'_n}{\sum_{i=1}^{n} x_i^* \omega'_i} \right\} \quad (16)$$

3. Case Study

3.1. General Features

In the paper, the navigation environment in the waters in the jurisdiction of Sanya, Hainan Province, PRC is taken as an example for analysis and study. The jurisdiction, with a coastline of 452.5 km, covers the navigable waters of five cities and counties in Southern Hainan, including Sanya, Lingshui, Leshan, Wuzhishan and Baoting.

Referring to the statistics of accidents within the jurisdiction of Sanya from 2010 to 2019, a total of 224 traffic accidents occurred within the jurisdiction of Sanya Maritime Safety Administration, including ship collision, ship grounding, ship damage, ship sinking, ship fire and others. The specific occurrence time and frequency are shown in Figures 2 and 3.

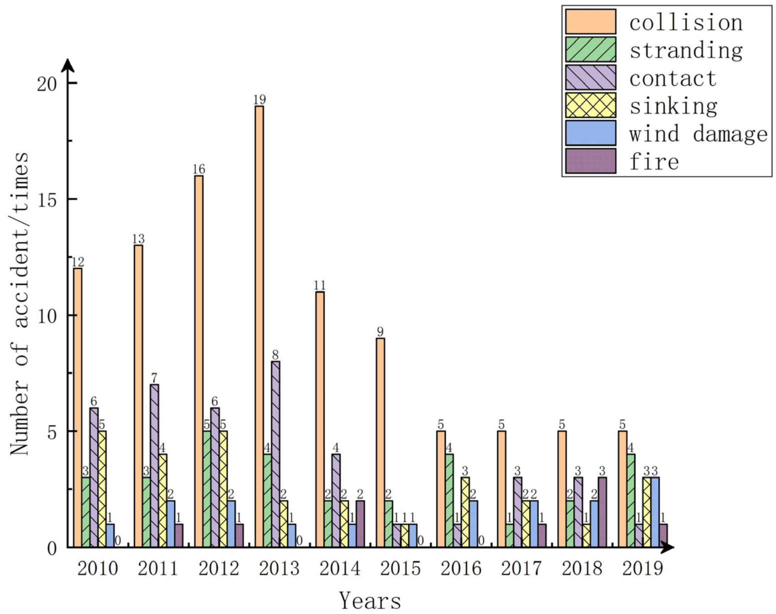

Figure 2. Number of accidents in different years.

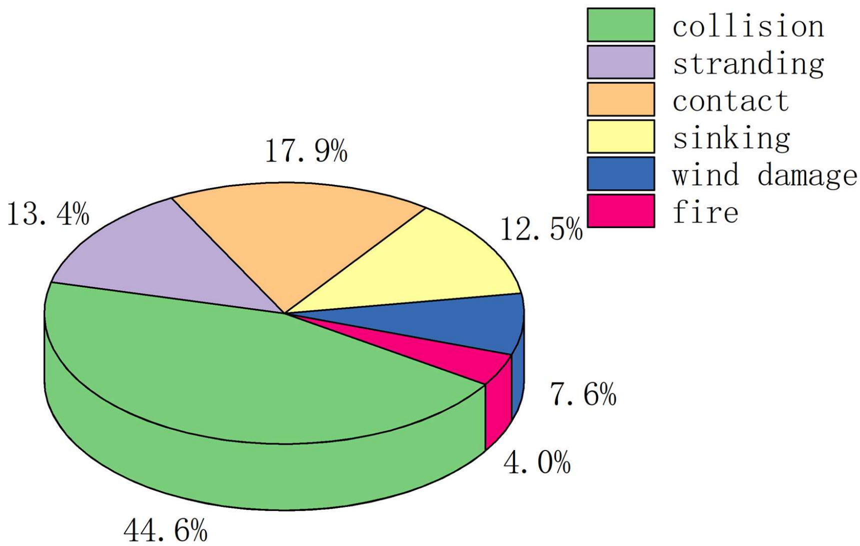

Figure 3. Occurrences of different types of accidents.

The main ships transiting within the jurisdiction are fishing vessels, passenger ships and cargo ships. According to the statistics of AIS, the number of ships entering and leaving the port every day is about 100. If fishing vessels without relevant equipment are counted, the daily flow of ships entering and leaving the port is more. Due to the wide variety and different generation mechanisms of maritime accidents, the collision accidents within the jurisdiction of Sanya in the last 10 years are taken as the study object, which can better reflect the impact of environmental factors in the same kinds of accidents. In the paper, the probability impact of environmental navigation factors on accident risk is determined by taking collision accidents within the jurisdiction of Sanya in the last 10 years as samples.

3.2. Calculation of Impact Probability

Considering the relationship between the total number of accident samples and grading, at least one accident can be assigned to the level of each environmental factor. See Table 4 for the grading of key levels of environmental navigation risk.

Table 4. Grading of the environmental impact factors of navigation.

Level of Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Wind (wind scale)	0~2	2~4	4~5	5~6	Above level 6
Flow (m/s)	0~1	1~1.5	1.5~2	2~2.5	2.5
Visibility (m)	Above 3000	1000~3000	500~1000	200~500	Below 200
Seaway width (m)	Above 500	300~500	200~300	100~200	Below 100
Seaway length (km)	30 and below	30~60	60~90	90~120	Above 120
Seaway curvature (°)	15 and below	15~30	30~45	45~60	Above 60
Seaway crossing (point)	1 and below	1~3	3~6	6~10	Above 10
Conditions of seaway obstruction (piece)	1 and below	1~3	3~7	7~13	Above 13
Ship traffic flow (ship/day)	Below 50	50~80	80~100	100~150	Above 150
Traffic flow density (vessel/square nautical mile)	Below 20	20–25	25–30	30–36	Above 36
Status of navigation aids	Very complete	Basically complete	Common	Partially deficient	Deficient

The quantification of the impact probability of environmental navigation factors can be carried out by Bayesian conditional probability. Assuming that a given event B has occurred, we want to know the possibility of another event A, which is reflected in the conditional probability of A in B. It is recorded as $P(A|B)$, that is:

$$P(A|B) = \frac{P(A)P(B|A)}{P(B)} \tag{17}$$

where $P(A|B)$ represents the probability of maritime accidents of ships when a certain impact factor (a certain level) exists in the statistical period; $P(B|A)$ stands for the existence probability of a certain impact factor (a certain level) when a maritime accident of ships occurs in the statistical period; $P(A)$ signifies the probability of maritime accidents of ships in the statistical period; $P(B)$ indicates the inherent occurrence probability of the existence of an impact factor (level), which can be replaced by the occurrence frequency of a factor (level) in the statistical period.

Over the statistical period of 3650 days, 100 historical collision accidents in Sanya waters in the last ten years (about 3600 days) were statistically analyzed, and the values of $P(B|A)$ and $P(A)$ were calculated respectively, so that $P(B)$ is the impact probability of the impact factors of navigation environment on maritime accidents. The results are shown in Table 5.

The impact probability of the navigation environment here only refers to the contribution of the factor to accidents, but the occurrence of accidents is related not only to the accident impact probability from the factor, but also to the occurrence frequency of the factor itself.

Table 5. The impact probability of the impact factors of the navigation environment on accidents.

Level of Factors	Level 1	Level 2	Level 3	Level 4	Level 5
Wind	0.011	0.035	0.030	0.041	0.057
Flow	0.016	0.019	0.046	0.046	0.057
Visibility	0.009	0.022	0.037	0.050	0.071
Seaway width	0.059	0.020	0.008	0.035	0.059
Seaway length	0.045	0.023	0.015	0.028	0.055
Seaway curvature	0.044	0.024	0.017	0.033	0.042
Seaway crossing	0.044	0.019	0.019	0.044	0.040
Seaway obstruction	0.044	0.023	0.015	0.022	0.067
Ship traffic flow	0.025	0.026	0.024	0.029	0.048
Ship density	0.045	0.019	0.021	0.034	0.034
Allocation of navigation aids	0.045	0.015	0.025	0.019	0.052

3.3. Calculation of the Fused Weight Value

According to the dynamic weight evaluation model constructed in Section 3, the subjective and objective weights are calculated respectively and the fused weight value is obtained, which is used as the risk input value. The calculation process is shown as follows.

3.3.1. Subjective Weight Results

The occurrence frequency of the 11 impact factors in the jurisdiction with months is counted, and the subjective weight of the impact factors of different navigation environment in each month is adjusted by using the principle of inferior value tendency. Firstly, the proportion relationship p_{ij} of different impact factor levels of navigation environment in each month is calculated:

$$p_{ij} = \frac{t_{ij}}{t}(i = 1, 2, 3 \ldots, n; j = 1, 2, 3 \ldots, m) \tag{18}$$

where t_{ij} refers to the number of days that the i-th factor appears in the j-th grade in this month, and t represents the number of days in this month.

The composite value of the impact factor levels of different navigation environments in each month is calculated with the idea of weighted average. The proportional relationship of each month's environmental factor level is multiplied with its corresponding level; the sum value is the composite value of the impact factor level of the navigation environment in that month. Now, the composite value of the navigation factor in this month P_i is:

$$P_i = \sum_{j=1}^{m} p_{ij} \cdot j \cdot (j = 1, 2, 3 \ldots, m) \tag{19}$$

The adjustment values of the subjective weight for the key factors of navigation environment risk are shown in Table 6.

3.3.2. Objective Weight Results

The impact probability of the composite value level of the impact factors of navigation environment every month is calculated by using the interpolation method. Suppose that the composite value x of the impact factor level is now located between levels a and $a + 1$. At this time, the impact probability of level a is p_1, the impact probability of level $a + 1$ is p_2 and the impact probability of level x is p; then:

$$p = p_1 + \frac{(p_2 - p_1)(x - a)}{(a + 1) - a} = p_1 + (p_2 - p_1)(x - a) \tag{20}$$

The adjustment values of the objective weight for the key factors of navigation environment risk are shown in Table 7.

Table 6. Adjustment values of subjective weight.

Month	Wind	Flow	Visibility	Seaway Width	Seaway Length	Seaway Curvature	Seaway Crossing	Seaway Obstruction	Ship Traffic Flow	Ship Density	Status of Navigation Aids
January	0.062	0.066	0.066	0.099	0.099	0.098	0.098	0.104	0.102	0.109	0.097
February	0.058	0.063	0.067	0.098	0.100	0.098	0.098	0.106	0.100	0.112	0.099
March	0.057	0.064	0.070	0.099	0.099	0.098	0.098	0.102	0.100	0.114	0.098
April	0.064	0.069	0.066	0.101	0.097	0.100	0.100	0.095	0.096	0.111	0.102
May	0.098	0.088	0.092	0.095	0.092	0.094	0.094	0.090	0.081	0.084	0.093
June	0.101	0.084	0.092	0.094	0.093	0.096	0.096	0.091	0.074	0.080	0.099
July	0.097	0.089	0.092	0.094	0.093	0.095	0.095	0.091	0.069	0.085	0.098
August	0.102	0.086	0.087	0.095	0.092	0.094	0.094	0.092	0.075	0.085	0.097
September	0.086	0.082	0.096	0.099	0.095	0.098	0.098	0.096	0.071	0.079	0.100
October	0.065	0.069	0.080	0.097	0.099	0.097	0.097	0.104	0.087	0.105	0.099
November	0.067	0.062	0.061	0.098	0.101	0.100	0.100	0.104	0.097	0.113	0.098
December	0.062	0.057	0.056	0.101	0.104	0.102	0.102	0.107	0.100	0.110	0.100

Table 7. Adjustment values of objective weight.

Month	Wind	Flow	Visibility	Seaway Width	Seaway Length	Seaway Curvature	Seaway Crossing	Seaway Obstruction	Ship Traffic Flow	Ship Density	Status of Navigation Aids
January	0.176	0.059	0.118	0.059	0.059	0.059	0.059	0.059	0.118	0.118	0.118
February	0.133	0.067	0.133	0.067	0.067	0.067	0.067	0.067	0.067	0.133	0.133
March	0.133	0.067	0.133	0.067	0.067	0.067	0.067	0.067	0.067	0.133	0.133
April	0.188	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.125	0.125	0.125
May	0.167	0.167	0.167	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.111
June	0.167	0.167	0.167	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.111
July	0.167	0.167	0.167	0.056	0.056	0.056	0.056	0.056	0.056	0.056	0.111
August	0.176	0.176	0.118	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.118
September	0.176	0.118	0.176	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.118
October	0.200	0.067	0.133	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.133
November	0.200	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.133	0.133
December	0.214	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.143

3.3.3. Fusion Weight Results

The improved D-S evidence theory and grey relation analysis (GRA) are used to fuse the expert weight, subjective weight and objective weight. Finally, the adjusted fusion weight is calculated, as shown in Table 8. The comparative analysis of fused weight with subjective weight, objective weight and expert weight is shown in Figures 4–6.

Table 8. The adjustment values of the fused weight for key impact factors.

Month	Wind	Flow	Visibility	Seaway Width	Seaway Length	Seaway Curvature	Seaway Crossing	Seaway Obstruction	Ship Traffic Flow	Ship Density	Status of Navigation Aids
January	0.126	0.130	0.089	0.074	0.075	0.076	0.075	0.080	0.093	0.093	0.090
February	0.100	0.131	0.099	0.074	0.076	0.076	0.076	0.082	0.082	0.104	0.100
March	0.100	0.131	0.099	0.075	0.076	0.077	0.076	0.079	0.082	0.104	0.100
April	0.134	0.132	0.059	0.076	0.075	0.078	0.077	0.076	0.098	0.099	0.096
May	0.126	0.140	0.121	0.072	0.071	0.073	0.073	0.075	0.082	0.082	0.086
June	0.126	0.139	0.121	0.072	0.072	0.074	0.074	0.075	0.081	0.081	0.086
July	0.125	0.140	0.121	0.071	0.071	0.074	0.073	0.075	0.081	0.082	0.086
August	0.134	0.143	0.092	0.074	0.072	0.075	0.074	0.077	0.083	0.083	0.092
September	0.127	0.134	0.124	0.073	0.072	0.074	0.074	0.074	0.080	0.080	0.089
October	0.138	0.129	0.098	0.072	0.074	0.075	0.074	0.080	0.081	0.081	0.098
November	0.140	0.131	0.058	0.074	0.077	0.078	0.077	0.081	0.082	0.104	0.100
December	0.147	0.130	0.058	0.076	0.079	0.079	0.078	0.082	0.082	0.085	0.105

As seen in Figures 4–6, the expert weight of indexes does not change with the change in months, while the subjective weight and objective weight obviously change with the change in months, among which the weights of wind, flow, visibility, ship traffic flow and ship density change most obviously with the change in months. The change trend of the fused weight basically not only conforms to the changes of the other three weight curves, but also has weight characteristics calculated with the other three methods. Finally, the method can effectively reflect the expert weight, subjective weight and objective weight of indexes, and has good reference value.

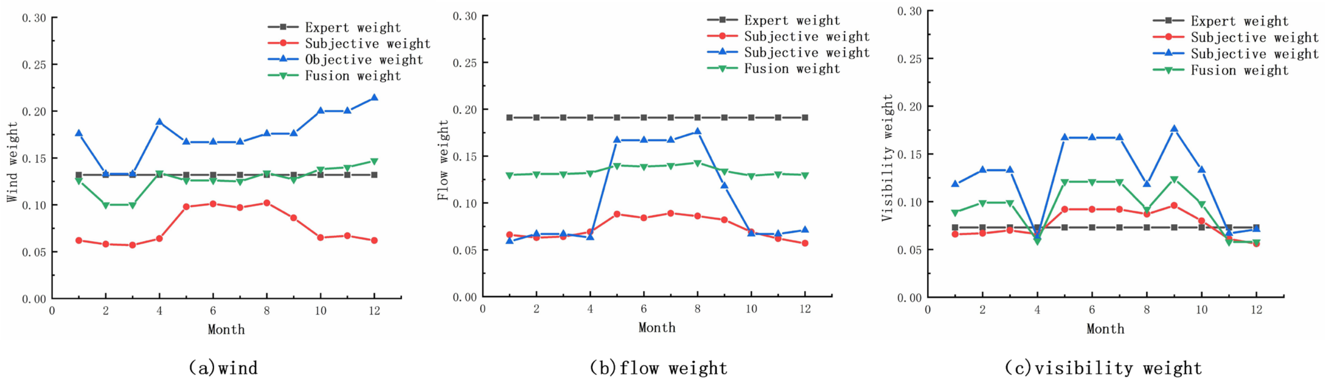

Figure 4. Weight values of sea conditions environmental factors.

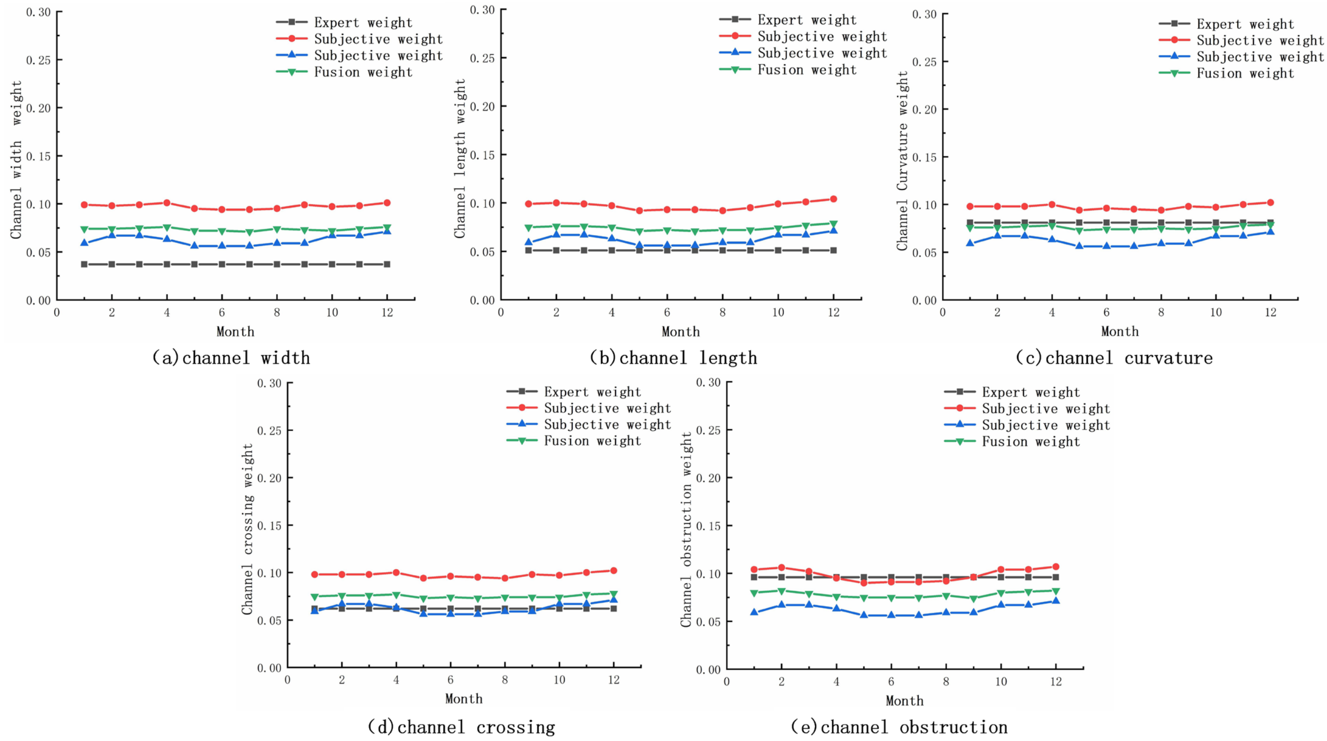

Figure 5. Weight values of seaway conditions factors.

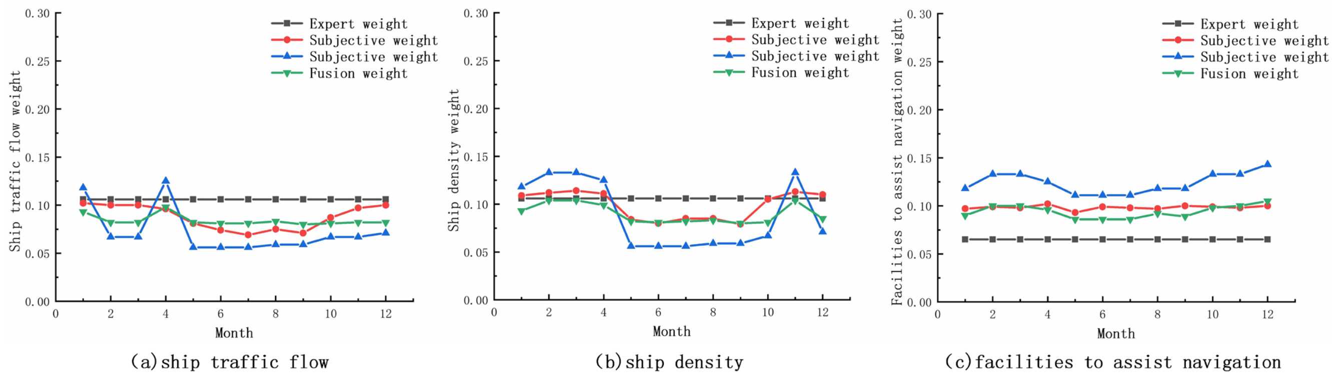

Figure 6. Weight values of traffic environment factors.

3.4. Risk Calculation

Through the definition of risk [21], the risk value r_i of the i-th impact factor of navigation environment is calculated as follows:

$$r_i = \omega_i \cdot \chi_i \tag{21}$$

where χ_i is the impact probability corresponding to the composite value of the impact factor level of navigation environment, and ω_i is the adjustment value of weight after dynamic weight fusion.

The monthly risk value R of navigation environment in the waters in the jurisdiction is:

$$R = \sum_{1}^{n} r_i \tag{22}$$

According to the calculation results of the impact probability of the impact factors of navigation environment in Section 3.2, the fused weight value in Section 3.3 and the definition of risk, the risk value of a single impact factor (which changes with the change in months) of the navigation environment in the waters where the study is carried out is obtained, as shown in Table 9.

Table 9. Statistical table of the risk value of the single impact factor of navigation environment which changes with the change in months.

Month	Wind	Flow	Visibility	Seaway Width	Seaway Length	Seaway Curvature	Seaway Crossing	Seaway Obstruction	Ship Traffic Flow	Ship Density	Status of Navigation Aids
January	0.0040	0.0024	0.0019	0.0006	0.0011	0.0013	0.0014	0.0013	0.0023	0.0024	0.0022
February	0.0028	0.0024	0.0021	0.0007	0.0012	0.0014	0.0014	0.0018	0.0020	0.0026	0.0025
March	0.0028	0.0024	0.0023	0.0006	0.0012	0.0014	0.0014	0.0012	0.0020	0.0028	0.0025
April	0.0044	0.0026	0.0012	0.0006	0.0012	0.0014	0.0015	0.0013	0.0024	0.0025	0.0024
May	0.0039	0.0055	0.0042	0.0006	0.0011	0.0013	0.0014	0.0013	0.0021	0.0017	0.0021
June	0.0039	0.0047	0.0041	0.0006	0.0011	0.0013	0.0014	0.0013	0.0021	0.0016	0.0022
July	0.0038	0.0054	0.0041	0.0006	0.0011	0.0013	0.0014	0.0013	0.0021	0.0017	0.0022
August	0.0043	0.0052	0.0030	0.0006	0.0012	0.0013	0.0014	0.0013	0.0021	0.0017	0.0023
September	0.0041	0.0042	0.0044	0.0006	0.0011	0.0013	0.0014	0.0012	0.0021	0.0016	0.0022
October	0.0048	0.0027	0.0027	0.0006	0.0011	0.0013	0.0014	0.0013	0.0020	0.0019	0.0025
November	0.0049	0.0024	0.0011	0.0006	0.0012	0.0013	0.0014	0.0013	0.0020	0.0028	0.0025
December	0.0046	0.0023	0.0010	0.0006	0.0012	0.0014	0.0015	0.0013	0.0020	0.0021	0.0026

According to Table 9, the monthly risk change chart of each index is drawn, as shown in Figures 7 and 8.

Compared with the traditional risk assessment methods, this model can better reflect the dynamic changes of the risks of navigation environment factors. The standard values of the impact factor levels of different navigation environments for every month and the impact probability corresponding to the standard value are known from the aforementioned calculation. The risk values of different indexes changing with the change in months are shown in Figure 7. Seen from Figure 7, wind, flow and visibility are basically the three impact factors with the highest monthly risk proportion, among which wind is at a lower risk value in February and March and is higher in other months, while flow and visibility are at a high risk level from May to September. The monthly navigation environment risk in the waters in the jurisdiction is also obtained. The risk of the navigation environment in the waters in the jurisdiction, which changes with the change in months, is shown in Figure 8. According to the Figure 8, the minimum value (i.e., 0.0206) of navigation environment risk in the waters in the jurisdiction occurs in March and December, while the maximum risk value occurs in May, followed by July. The risk values in both months are greater than 0.025.

According to the meteorological statistics of the jurisdiction, typhoons occur frequently in May to August. Although May to August is the closed fishing season and the number of fishing vessels is reduced, the waters are dominated by cargo ships and passenger ships.

Although the decrease in the number of fishing vessels leads to the relative decrease in traffic flow and ship density, the risk of navigation environment caused by bad meteorological environment exceeds the improvement of the traffic that is caused by the decrease of ships. According to the accident statistics within the jurisdiction, the high-frequency period of maritime accidents is from May to August. The final conclusion obtained in the paper is in line with the characteristics of the navigation environment within the jurisdiction. The risk value of the navigation environment within a specific jurisdiction, which changes with the change in months, can be obtained with the method, and the method features repeatability and operability. The evaluation results in the paper are highly consistent with the characteristics of historical accidents and the navigation environment within the jurisdiction, and so they have strong applicability.

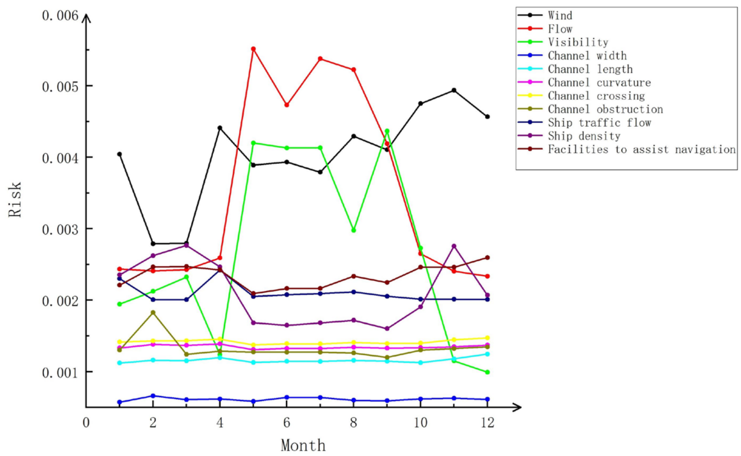

Figure 7. Schematic diagram of the risk value of different indexes, which changes with the change in months.

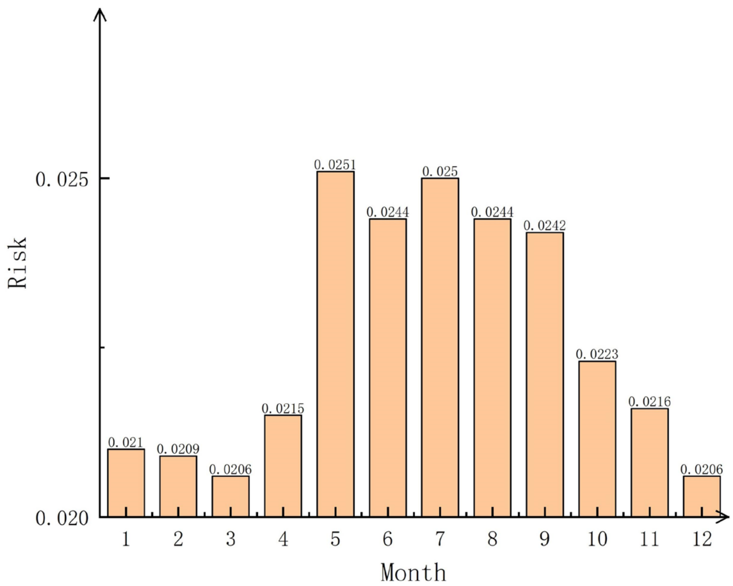

Figure 8. Changes of overall risk of navigation environment in waters in the jurisdiction with the change in months.

4. Conclusions

This paper aims at some practical problems, such as static and subjective risk evaluation of navigation environments, which easily occurs when the data samples of objective historical accidents are insufficient. A dynamic weight evaluation model of navigation environment safety risk based on the fusion of subjective and objective impact factors is established in this paper and an example application is carried out. With the statistical data of historical maritime accidents as the research basis, the impact probability of the key impact factors of navigation environment on accidents is extracted by tapping and studying the objective law of accident samples, and the key environmental factors influencing the safety risk of navigation are obtained by screening. The subjective weight adjustment based on the subjective grade change of the actual navigation environment factors is determined according to the change in the impact probability of accidents, which is caused by the dynamic change of the actual navigation environment factors. Finally, the risk model based on the accident impact probability, and the fused weight of each navigation environment factor is established according to the dynamic weight fusion based on the improved D–S evidence theory and grey correlation analysis. Meanwhile, the impact probability of key elements of navigation environment risk in the waters of Sanya is calculated in the paper, as is the fused weight of each element by using the constructed dynamic weight evaluation model. The dynamic evolution process of the navigation environment in the waters of Sanya every month was evaluated quantitatively, with results showing that the comprehensive navigation environment risk in the jurisdiction maintains a high level from May to September. This conclusion is not only highly consistent with the results based on the statistics of historical accidents and the analysis of the characteristics of the navigation environment in the jurisdiction, but is also better than the results of the static safety evaluation of the navigation environment and the dynamic safety evaluation based on the process, thus verifying the effectiveness and accuracy of the application of the model.

The content of this paper can enrich the understanding of dynamic risk evaluation of navigation environments, in order to more comprehensively and intuitively evaluate the navigation environment risk based on the current safety situation of waters, objectively increase the safety of navigation environment in the waters and improve the reliability of ship navigation. Meanwhile, it also provides a theoretical reference for maritime authorities to understand and provide warnings on the safety of the navigation environment to a certain extent.

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References

1. Huang, Y.; Chen, L.; Chen, P.; Negenborn, R.R.; van Gelder, P.H.A.J.M. Ship collision avoidance methods: State-of-the-art. *Saf. Sci.* **2020**, *121*, 451–473. [CrossRef]
2. Sun, H.; Hao, Y.; Qu, J.; Zhu, P.; Tao, R. Study on the Model of Construction Safety Risk Evaluation Coupling Multiple Factors in Navigable Waters. In *Sustainable Development of Water and Environment, Proceedings of the International Conference on Sustainable Development of Water and Environment, Bangkok, Thailand, 12–13 March 2021*; Springer: Cham, Switzerland, 2021; pp. 321–333.
3. Chen, Y.; Xie, C.; Chen, S.; Huang, L. A New Risk-based Early-warning Method for Ship Collision Avoidance. *IEEE Access* **2021**, *9*, 108236–108248. [CrossRef]
4. Deng, J.; Liu, S.; Xie, C.; Liu, K. Risk Coupling Characteristics of Maritime Accidents in Chinese Inland and Coastal Waters Based on NK Model. *J. Mar. Sci. Eng.* **2021**, *10*, 4. [CrossRef]
5. Xie, C.; Huang, L.; Wang, R.; Deng, J.; Shu, Y.; Jiang, D. Research on quantitative risk assessment of fuel leak of LNG-fuelled ship during lock transition process. *Reliab. Eng. Syst. Saf.* **2022**, *221*, 108368. [CrossRef]

6. Chen, S.; Gong, B.; Xie, C.; Liu, C.; Liu, Z.; Wang, R. Modeling of Ship Encounter Risk Based on Riemann Sphere Projection Transformation. *IEEE Access* **2022**, *10*, 42554–42565. [CrossRef]
7. Wang, J.; Li, M.; Liu, Y.; Zhang, H.; Zou, W.; Cheng, L. Safety assessment of shipping routes in the South China Sea based on the fuzzy analytic hierarchy process. *Saf. Sci.* **2014**, *62*, 46–57. [CrossRef]
8. Başhan, V.; Demirel, H.; Gul, M. An FMEA-based TOPSIS approach under single valued neutrosophic sets for maritime risk evaluation: The case of ship navigation safety. *Soft Comput.* **2020**, *24*, 18749–18764. [CrossRef]
9. Tengesdal, T.; Johansen, T.A.; Brekke, E.F. Ship Collision Avoidance Utilizing the Cross-Entropy Method for Collision Risk Assessment. *IEEE Trans. Intell. Transp. Syst.* 2021. *early access*. [CrossRef]
10. Yunlong, W.; Kai, L.; Guan, G.; Yanyun, Y.; Fei, L. Evaluation method for Green jack-up drilling platform design scheme based on improved grey correlation analysis. *Appl. Ocean Res.* **2019**, *85*, 119–127. [CrossRef]
11. Liu, R.W.; Liang, M.; Nie, J.; Lim, W.Y.B.; Zhang, Y.; Guizani, M. Deep Learning-Powered Vessel Trajectory Prediction for Improving Smart Traffic Services in Maritime Internet of Things. *IEEE Trans. Netw. Sci. Eng.* **2022**. *early access*. [CrossRef]
12. Zhang, G.; Thai, V.V. Expert elicitation and Bayesian Network modeling for shipping accidents: A literature review. *Saf. Sci.* **2016**, *87*, 53–62. [CrossRef]
13. Li, Z.; Yao, C.; Zhu, X.; Gao, G.; Hu, S. A decision support model for ship navigation in Arctic waters based on dynamic risk assessment. *Ocean Eng.* **2022**, *244*, 110427. [CrossRef]
14. Zhang, M.; Zhang, D.; Goerlandt, F.; Yan, X.; Kujala, P. Use of HFACS and fault tree model for collision risk factors analysis of icebreaker assistance in ice-covered waters. *Saf. Sci.* **2019**, *111*, 128–143. [CrossRef]
15. Szlapczynski, R.; Szlapczynska, J. An analysis of domain-based ship collision risk parameters. *Ocean Eng.* **2016**, *126*, 47–56. [CrossRef]
16. Kim, D.H. Identification of collision risk factors perceived by ship operators in a vessel encounter situation. *Ocean Eng.* **2020**, *200*, 107060. [CrossRef]
17. Fan, C.; Wróbel, K.; Montewka, J.; Gil, M.; Wan, C.; Zhang, D. A framework to identify factors influencing navigational risk for Maritime Autonomous Surface Ships. *Ocean Eng.* **2020**, *202*, 107188. [CrossRef]
18. Saaty, T.L. Decision making with the analytic hierarchy process. *Int. J. Serv. Sci.* **2008**, *1*, 83–98. [CrossRef]
19. Fujii, Y.; Shiobara, R. The analysis of traffic accidents. *J. Navig.* **1971**, *24*, 534–543. [CrossRef]
20. MacDuff, T. The probability of vessel collisions. *Ocean Ind.* **1974**, *9*, 144–148.
21. Chen, P.; Huang, Y.; Mou, J.; van Gelder, P. Probabilistic risk analysis for ship-ship collision: State-of-the-art. *Saf. Sci.* **2019**, *117*, 108–122. [CrossRef]