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Navigation Risk Assessment of Autonomous Ships Based on Entropy—TOPSIS—Coupling Coordination Model

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Abstract: An autonomous ship refers to a ship that achieves autonomous operation in ship navigation, management, maintenance, cargo transportation and other aspects. Due to the uncertainty in the risks posed by autonomous ship navigation, its risk assessment attracts great attention from researchers. By analyzing the historical accident statistics, this paper gives a comprehensive analysis from the perspective of "Man-Ship-Environment-Management". In addition, a quantitative evaluation method based on the Entropy–TOPSIS–Coupling coordination model is proposed, which presents a comprehensive assessment of the risks of autonomous ship navigation safety. Furthermore, scientific forecasts and suggestions for improvement are put forward according to the evaluation results.

Keywords: autonomous ships' navigation safety; risk assessment; entropy weight method; TOPSIS method; coupling coordination model

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1. Introduction

As the most important mode of transportation, the safety of maritime transportation has acquired extensive attention from society. To further ensure the safety of maritime cargo transportation, reduce the labor and operating costs, and promote the continuous growth of trade volume and economic benefits, the autonomous ship has emerged as the times require. However, the navigation risk of autonomous ships is an inevitable problem [1–4]. Therefore, the way to identify the navigation risks of autonomous ships and to take targeted measures to reduce the probability of traffic accidents and possible losses is of great significance for ensuring the navigation safety of autonomous ships and improving the navigation environment. Through the prediction of navigation risk and dealing with navigation hazards properly, the results of the risk evaluation will provide a reliable theoretical and practical support for a sustainable development of autonomous ships.

Currently, navigation risk assessment methods are mainly carried out on traditional manned ships, whereas autonomous ship risk assessment methods are rarely considered. In the risk assessment [5–8], the International Maritime Organization (IMO) introduced and applied methods and concepts of standardized Formal Safety Assessment (FSA) to the maritime community. Moreover, they requested that the member states actively carry out applied research in the field of ship safety.

In 2015, Zhao et al. [9] first summarized the evaluation methods for ship safety from the perspective of analysis tools and research approaches, then divided them into five categories: (1) Evaluation methods based on probability theory and mathematical statistics. E.g., Hu et al. [10] first introduced the probabilistic impact map into the safety assessment of offshore platforms and verified its applicability. However, this kind of method focuses on investigating the navigation safety status based on the accident occurrence, which leads to some difficulties in generating a comprehensive assessment. Moreover, the safety assessment obtained by this method remains in the post-evaluation stage because of the seldom consideration of system risk factors. (2) Evaluation methods based on logical reasoning, including fault tree analysis [11], Bayesian analysis [12] and other methods. This kind of evaluation can analyze the influence degree and correlation degree of various risk factors. Moreover, it is easy to find potential problems and it is conducive to formulating targeted safety improvement measures. However, the reasoning process is complex and the workload is large, while the evaluation accuracy strictly depends on the relationship between events. (3) Evaluation methods based on fuzzy theory. The comprehensive fuzzy evaluation system was first established by Wang et al. [13] in 2004. Furthermore, the gray theory analysis method was first proposed by Zhang et al. [14] in 2013 for the navigation safety assessment of ships in heavy wind and waves. However, this kind of method has some defects such as subjective intervention and limited sample data. (4) Evaluation methods based on neural networks. This kind of method can effectively solve the nonlinear mapping between evaluation objectives and factors. Moreover, it can overcome the impact of subjective factors. However, the evaluation process is invisible and the evaluation results are relatively simple, which cannot fully describe the security situation. (5) Evaluation methods based on Formal Safety Assessment (FSA) [5]. This kind of method is a systematic and standardized comprehensive evaluation method. According to the characteristics of the system, reasonable indicators and methods can be selected at different stages of the evaluation. Therefore, it has strong flexibility and compatibility.

On the basis of the conventional research on the navigation safety of manned ships, this paper mainly focuses on the characteristics of autonomous ships. First, analyzing factors compromising safety including perception ability, remote control ability, environmental risk factors and situation judgment management, a navigation risk evaluation index system is established based on a more comprehensive perspective of "Man-Ship-Environment-Management". Second, the entropy weight method is used to calculate the navigation risk evaluation index weights. Subsequently, the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) and the coupling coordination degree model are deployed to analyze the interaction between the index factors in two dimensions, so as to obtain the evaluation grade of autonomous ships' navigation risk. Moreover, TOPSIS is a method of ranking according to the proximity between a limited number of evaluation objects and the idealized target. This proximity helps in evaluating the relative advantages and disadvantages of the existing objects. The coupling coordination degree model is used to analyze the coordinated development level of objects. Thus, the coupling degree refers to the interaction between two or more objects and the dynamic relationship between them to achieve coordinated development, which can reflect the degree of interdependence and mutual restriction between objects. Finally, scientific countermeasures and suggestions can be put forward according to the evaluation results. As there are not many autonomous ships in operation today, ordinary ship accidents have been considered as autonomous ship accidents in this paper.

2. Factors Affecting Navigation Safety

According to reference [15], the navigation risk factors of autonomous ships mainly come from four elements: ship factors, shore-based remote control factors, environmental factors and emergency management factors.

(1) Ship factors

The most important equipment that ensures the navigation safety of autonomous ships is the perception equipment. Ship factors include the perception equipment and its capability as well as the dynamic object sensing reliability, the static object sensing reliability, the object navigation state, and the ability of data fusion. The complex navigation environment will inevitably interfere with the perception ability of autonomous ships, for example, inaccurate measurement of undersea hydrological sensing instruments, return data affected by clutter, loss of dynamic target perception caused by bad weather, association ambiguity obstacle of data fusion caused by sensor measurement error, data deviation caused by aging or damage of equipment, etc. All these factors may cause the perception equipment to make wrong calculations, which will ultimately lead to accidents [16].

(2) Shore-based remote control factors

As we know, the normal navigation of autonomous ships depends on the 24 h safe control and supervision of the remote control center. The shore-based remote control factors mainly include human factors and technical factors.

(a) Human factors

Human factors mainly refer the low quality of personnel, for instance, lacking a sense of responsibility or proficient driving skills, lacking effective measures of preventing and controlling the accident, etc. [17].

(b) Technical factors

The technical factors consist of the communication between the ship and the shore, the reproduction ability of ship and shore navigation scene, network security, etc. The communication factors between the ship and the shore mainly include the transmission capability, transmission reliability and timeliness of the control command between ship and shore, and the reliability of onboard command execution. The situation awareness ability can also lead to the threat. The abnormal input data of the perception system, which is caused by the instability of the ship network, results in the inability to make efficient and accurate decisions. The network security factors mainly focus on preventing a cyber-attack on onboard systems, control systems and equipment and interference with satellite navigation communications and data transmission [18].

(3) Environmental factors

The complicated navigation environment is an important factor affecting the occurrence of ship navigation accidents. The environmental factors that may cause accidents mainly include poor visibility, fierce wind and rainstorm, thunder and lightning, weak light, dense ship flows, unobvious and inaccurate navigation aid marking, insufficient surplus water depth, low utilization and poor environment of the port, limited flow velocity, frequent swells, etc. [19].

(4) Emergency management factors

When ships encounter emergencies such as bad sea conditions, pirate attacks, fire, and water ingress, effective emergency management often determines whether losses and environmental pollution can be minimized in a timely manner. The emergency management factors that cause accidents mainly include management regulations or deficiencies in the management process. For example, the lack of laws and ship safety production regulations, the lack of emergency plan preparation and emergency drill management, the lack of security defense measures, the inaccurate emergency dispatching orders, and the insufficient emergency response are common factors. Similar to traditional manned ships, autonomous ships are more likely to miss the opportunity to make up for losses in the case of an emergency when the rescue cannot arrive in time [20].

3. Navigation Risk Assessment of Autonomous Ships Based on Entropy–TOPSIS–Coupling Coordination Model

3.1. Construction of Navigation Risk Assessment Index

Generally, the expert survey method [21], namely the Delphi method, is used to construct the navigation safety risk evaluation index system.

First, according to the expert opinion consultation, this paper analyzed traditional ships accident statistics from 2001 to 2021. Then, 609 traditional ship accident data were transformed into 262 accident data that match autonomous ships. In the specific research process, 10 experts were selected and two expert groups were established. The first group of experts includes the investigators of the maritime agency, the staff engaged in ship management, the staff engaged in the safety management of the classification society, the researchers of the Academy of Water Sciences, the captain of ocean transportation, etc. The selected experts have more than 10 years of work and management experience and have a deep understanding of traditional ship and modern intelligent ship navigation risk management. The second group of experts includes professors and associate professors of well-known maritime colleges, senior engineers of the Institute of Unmanned Ships, researchers of the Institute of Ship Management and senior engineers of the Institute of Ship Design. This paper first counts 609 maritime traffic accidents caused by ships, people, environment and management from 2001 to 2021 released by the China Maritime Safety Administration in a period of years, forming the original data of traditional ship navigation safety accidents. Then, expert group 1 analyze the specific risk factors causing these accidents from four aspects: navigation environment perception (ship), remote control center (person), environment and emergency management. Then, expert group 2 analyze the risk factors obtained by the first group again and then analogize and match the extracted risk factors with the autonomous ship to find out the risk factors that may cause the maritime traffic accidents of the autonomous ship in line with the characteristics of the autonomous ship. Finally, through the comparison of the historical ship accident data obtained by two groups of experts, 262 maritime traffic accidents in line with the characteristics of autonomous ships are indirectly obtained. It should be noted in particular that autonomous ships engaged in maritime transportation in the real sense are still under continuous research. In order to facilitate the research, only relevant risk factors can be extracted from historical data and relevant assumptions can be processed, just to verify the effectiveness of the model.

Then, the Delphi method [22] was applied to screen, simplify and synthesize the risk index. Specifically, the number of accidents caused by ship factors, shore-based remote control factors, environment factors and emergency management factors in each year are counted as $u_{j,i}$. Here, j is the year (1 to n = 21) and i is the risk factors identified in Section 2 (1 to m = 4). Therefore, the risk factors index matrix can be defined as $R_0 = [u_{j,i}]_{n\times m}$:

$$R_0 = [u_{j,i}]_{n\times m} = \begin{bmatrix} u_{1,1} & u_{1,2} & \cdots & u_{1,m} \\ u_{2,1} & u_{2,2} & \cdots & u_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ u_{n,1} & u_{n,2} & \cdots & u_{n,m} \end{bmatrix} \tag{1}$$

The relative occurrence of one type of accident in a given year compared to all accidents in the period of the same type is as follows:

$$t_{j,i} = \frac{u_{j,i}}{\sum\limits_{j} u_{j,i}} \tag{2}$$

3.2. Calculation of Navigation Risk Factors Index Weight

The entropy weight method [23,24] has the advantage of being able to find the inherent information in the risk factors index when calculating the weight of each indicator apart. At the same time, it can screen the evaluated indicators, and the calculated weights are relatively objective. Therefore, the entropy weight method is used to calculate the navigation risk factors index weight.

In this section, the weight of the risk factors i in year j is calculated. The smaller the entropy value is, the greater the index weight will be.

First, the risk factors index matrix is normalized. The normative matrix $R_1 = [r_{j,i}]_{n\times m}$ is as follows:

$$r_{j,i} = \frac{(u_{j,i})_{\max} - u_{j,i}}{(u_{j,i})_{\max} - (u_{j,i})_{\min}}, \forall j, i \tag{3}$$

where $r_{j,i} \in [0,1]$ and $(u_{j,i})_{\max}$ and $(u_{j,i})_{\min}$ are the maximum and minimum values of $u_{j,i}$.

The information entropy value e_i of risk factors i is as follows:

$$\begin{gathered} e_i = -\tfrac{1}{\ln n} \sum_{j=1}^{n} (f_{j,i} \times \ln f_{j,i}), \\ f_{j,i} = r_{j,i} / \sum_{j=1}^{n} r_{j,i},\ \forall i, j \end{gathered} \tag{4}$$

When $f_{j,i} = 0$, $\lim_{f_{j,i} \to 0} f_{j,i} \times \ln(f_{j,i}) = 0$. The index weight of each of the risk factors i is calculated by the information entropy as follows:

$$\widetilde{\omega}_i = [1 - e_i] / \left[m - \sum_{i=1}^{m} e_i \right], \forall i \tag{5}$$

3.3. Calculation of Navigation Risk Comprehensive Evaluation Index and Coupling Coordination Degree

In practical applications, it is usually necessary to comprehensively consider the risk factors of the overall safety system of the ship. The management and the control of ship accidents has shown a trend of changing the vertical single point data statistics to horizontal composite data comprehensive analysis. Therefore, this paper combines the horizontal and vertical dimensions to comprehensively evaluate the navigation risk of autonomous ships.

Concretely, the comprehensive risk evaluation index represents the relative navigation risk, which belongs to the vertical dimension evaluation of navigation risk. It can analyze the trend of the navigation risk over time by calculating the value of each risk factor of the autonomous ships. The coupling coordination degree model [25–27] belongs to the internal horizontal evaluation of navigation risk. It comprehensively analyzes the coupling strength and coordinated development level of various risks, which can reflect the internal association between these risk factors and is used to analyze the weak links of navigation.

3.3.1. Calculation of Navigation Risk Comprehensive Evaluation Index

TOPSIS is a sorting method that approximates the ideal solution [28–33] and it is widely used for the comparison and selection of multiple schemes and indicators. Basically, according to the distance between the optimal solution and the positive and negative ideal solutions, the priority is ranked based on the combination of these two distance measures.

First, the weighted matrix $R_2 = [o_{j,i}]_{n \times m}$ is calculated as follows:

$$o_{j,i} = \widetilde{\omega}_i \times r_{j,i}, \forall i, j \tag{6}$$

Secondly, determine the optimal solution S_i^+ and the worst solution S_i^- of the weighted value of risk factors i:

$$\begin{aligned} S_i^+ &= \max(o_{1,i}, o_{2,i}, \ldots, o_{n,i}), \forall i \\ S_i^- &= \min(o_{1,i}, o_{2,i}, \ldots, o_{n,i}), \forall i \end{aligned} \tag{7}$$

Then, calculate the Euclidean distance between the weighted value of year j and the optimal solution and the worst solution as d_j^+, d_j^-, respectively:

$$\begin{aligned} d_i^+ &= \sqrt{\sum_{i=1}^{m} \left(o_{j,i} - S_i^+\right)^2}, \forall i, j \\ d_i^- &= \sqrt{\sum_{i=1}^{m} \left(o_{j,i} - S_i^-\right)^2}, \forall i, j \end{aligned} \tag{8}$$

Finally, the TOPSIS model is used to calculate the comprehensive evaluation index C_j of the navigation risk of autonomous ships in the year j and rank them.

$$C_j = \frac{d_j^-}{d_j^- + d_j^+}, \forall j \tag{9}$$

Here, $C_j \in [0, 1]$.

3.3.2. Calculation of Coupling Coordination Degree

The coupling coordination degree model is used to analyze the coordinated development level of objects, involving the calculation of three index values, namely, the coupling degree B, the comprehensive coordination index V and the coupling coordination degree K. Finally, the coupling coordination degree of each item is evaluated according to the value of K.

First, calculate the coupling degree B_j of accidents caused by multiple risk factors in the year j [28]:

$$B_j = \left\{ \frac{k \times \sum\left(t_{j,i'} \times t_{j,i}\right)}{\left(\sum t_{j,i}\right)^2} \right\}^{\frac{1}{k}}, \forall j,\ B_j \in [0,1] \tag{10}$$

Here, $2 \le k \le m$ is the adjustment coefficient, indicating the number of coupling risk factors. $t_{j,i'} \times t_{j,i}$ is the product of the probability of dangerous accidents occurring in any pair of coupled subsystems. The sum under the division is over i; the sum over the division is over i and i' both. This indicator is mainly used to evaluate the coupling degree between these risk factors. The greater the coupling degree, the more likely the accident will occur.

Secondly, calculate the comprehensive coordination index V_j of the relative probability of accident in the year j:

$$V_j = \widetilde{\omega}_1 t_{j,1} + \widetilde{\omega}_2 t_{j,2} + \ldots + \widetilde{\omega}_m t_{j,m},\ \forall j,\ \mathrm{V}_j \in [0,1] \tag{11}$$

This indicator reflects the orderly and disorderly development of autonomous ships' navigation risks every year.

Finally, the coupling coordination degree K_j of autonomous ships' navigation risk in the year j is computed. This indicator is mainly used to evaluate the coupling degree and orderly development of autonomous ships' navigation risks every year. The calculation formula is as follows:

$$K_j = \sqrt{B_j \times V_j},\ \forall j \tag{12}$$

The calculation process of the proposed autonomous ships risk assessment method is shown in Figure 1.

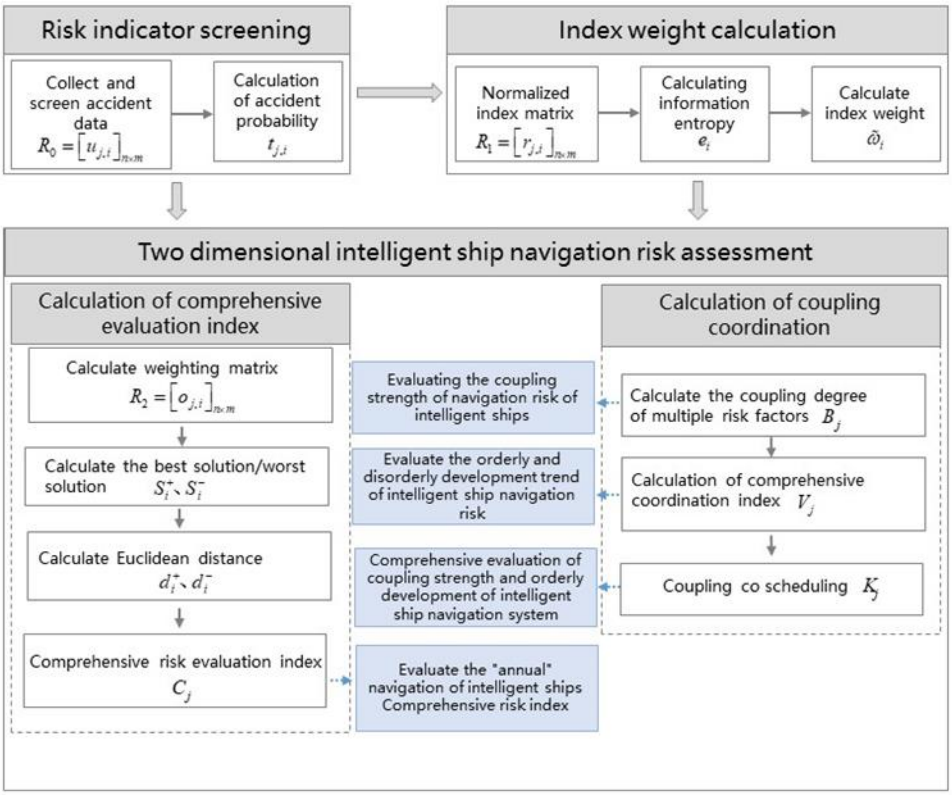

Figure 1. Calculation process of the Entropy–TOPSIS–Coupling coordination model.

4. Experiments and Analysis

4.1. Analysis of the Initial Data

To verify the effectiveness of the proposed evaluation method, simulations were executed on historical navigation accidents statistic data.

First, accidents caused by Ship (P)–Man (remote control factors, R)–Environment (E)–Management (M) from 2001 to 2021 were collected as the initial data of traditional ship navigation accidents, as shown in Table 1 and Figure 2. Secondly, by consulting experts, we confirmed the specific risk factors from four main factors: ship factors (P), shore-based remote control factors (R), environment factors (E) and emergency management factors (M). Then, 609 traditional ship accident data were transformed into 262 accident data that match autonomous ships, as shown in Table 2 and Figure 3. Before 2010, ships still lacked autonomous auxiliary equipment. With the development of science and technology, more autonomous auxiliary equipment was used on traditional ships. We also know that, when these intelligent devices were first put into use, both the proficiency of the operators and the defects of the equipment itself were not mature, so the maritime traffic accidents caused by them also increased. With the continuous proficiency in operation and the improvement of some equipment defects in the process of use, the resulting maritime traffic accidents also decreased. That is to say, in the statistical data, there was a peak around 2010. By analogy, it can be predicted that the number of accidents that may occur in the initial stage of the development of smart ships will increase in the future and will peak at a certain time. With the continuous improvement and maturity of relevant technologies, the number of accidents will decline.

Table 1. Initial statistics of traditional ship navigation accidents.

Year j \ Factor i	P	R	E	M	Total
2001	5	11	7	9	32
2002	9	11	9	7	36
2003	15	11	9	9	44
2004	11	9	9	11	40
2005	9	9	7	9	34
2006	9	7	7	9	32
2007	11	9	7	9	36
2008	9	7	9	7	32
2009	7	11	8	9	35
2010	13	13	11	13	50
2011	9	17	9	9	44
2012	5	9	5	7	26
2013	7	7	5	5	24
2014	3	5	7	5	20
2015	5	5	7	7	24
2016	3	5	5	5	18
2017	3	5	3	5	16
2018	3	5	5	7	20
2019	3	7	3	5	18
2020	5	3	3	5	16
2021	3	3	3	3	12
$\sum$	147	169	138	155	609

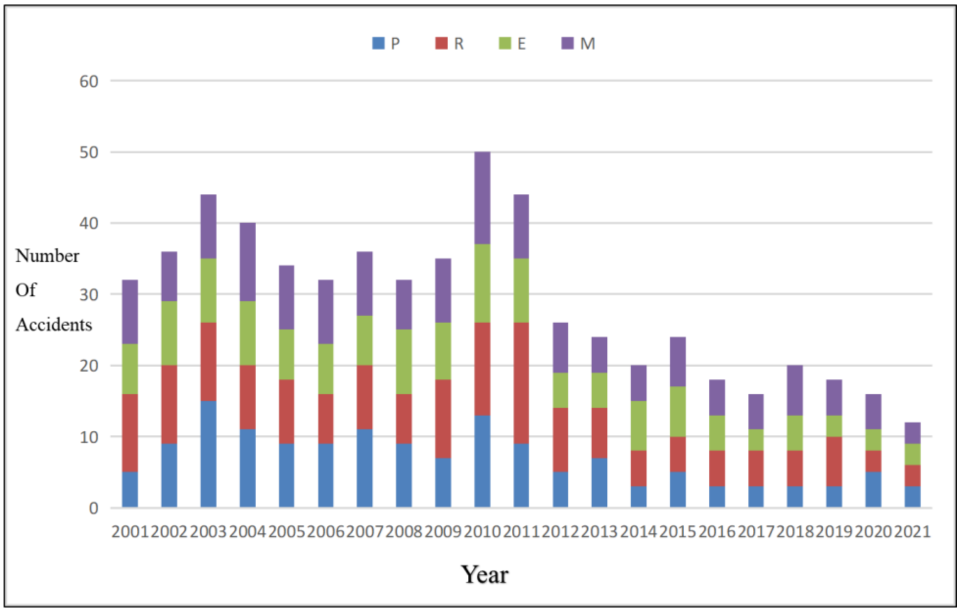

Figure 2. Statistics of traditional ship accidents caused by corresponding risk factors.

Table 2. Statistics of autonomous ship navigation accidents.

Factor *i* / Year *j*	P	R	E	M	Total
2001	2	5	3	4	14
2002	4	5	4	3	16
2003	7	5	4	4	20
2004	5	4	4	5	18
2005	4	4	3	4	15
2006	4	3	3	4	14
2007	5	4	3	4	16
2008	4	3	4	3	14
2009	3	5	3	4	15
2010	6	6	5	6	23
2011	4	8	4	4	20
2012	2	4	2	3	11
2013	3	3	2	2	10
2014	1	2	3	2	8
2015	2	2	3	3	10
2016	1	2	2	2	7
2017	1	2	1	2	6
2018	1	2	2	3	8
2019	1	3	1	2	7
2020	2	1	1	2	6
2021	1	1	1	1	4
$\sum$	63	74	58	67	262

The following can be seen from the statistical results in Tables 1 and 2: (1) From 2001 to 2021, the number of navigation accidents caused by man factors (R) was the largest, which is 169 in Table 1 and 74 in Table 2. It shows that, for both traditional ships and autonomous ships, the influence of human factors cannot be ignored; (2) The impact of environmental factors (E) on marine traffic did not decrease significantly with the development of science and technology, but increased in a certain period of time.

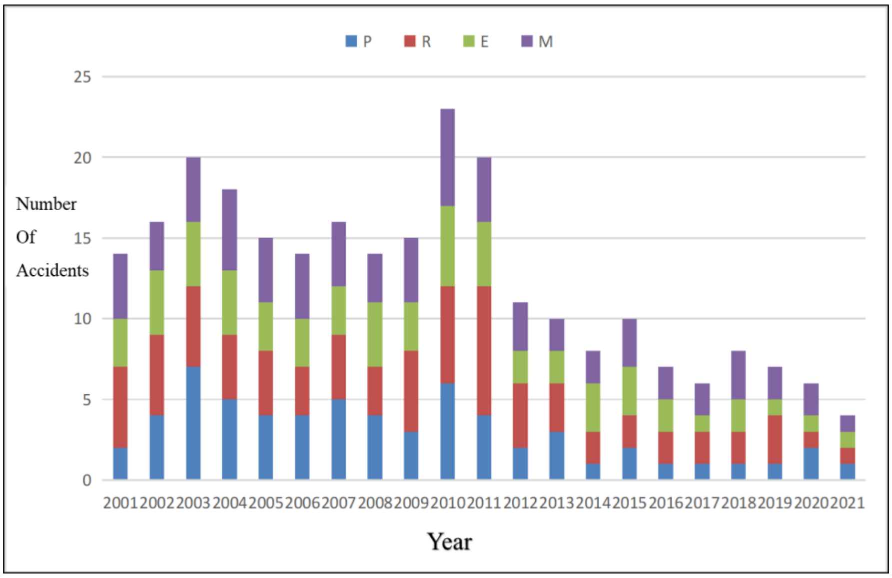

Figure 3. Statistics of autonomous ship accidents caused by corresponding risk factors.

4.2. Analysis of the Vertical Evaluation Results

The comprehensive risk evaluation index C_j reflects the degree of navigation safety, which belongs to the vertical evaluation dimension. The smaller the value is, the more unsafe the navigation is. As shown in Table 3 and Figure 4, the comprehensive risk evaluation index declines first, reaches a minimum and then shows an upward trend. Therefore, it can be predicted that the number of autonomous ship navigation accidents will increase at the initial stage, and there will be a peak at a certain period. With the continuous improvement of related technologies, the number of accidents will decline. Because the data screened by the research institute are highly related to the marine traffic accident data of autonomous ships, they can reflect one of the conditions of autonomous ships to a certain extent. The comprehensive risk assessment index reflects the size of navigation safety. The smaller the score is, the more unsafe the navigation is. As shown in the study, the comprehensive risk assessment index was the smallest in 2010 and 2011, indicating that more maritime traffic accidents occurred at that time, which is also consistent with the specific study. After 2011, the comprehensive risk assessment index increased, indicating that the number of maritime traffic accidents also decreased.

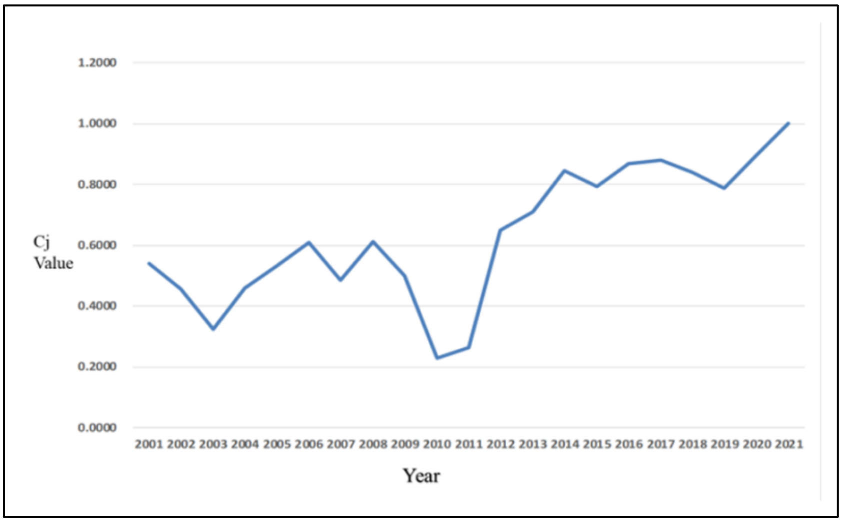

Figure 4. Visualization of the comprehensive risk evaluation index C_j.

Table 3. Ranking of the comprehensive risk evaluation index C_j.

Year \ Result	d_j^+	d_j^-	c_j	Sorting by c_j
2001	0.1963	0.2315	0.5412	13
2002	0.2200	0.1852	0.4570	18
2003	0.2938	0.1405	0.3236	19
2004	0.2261	0.1909	0.4578	17
2005	0.1889	0.2146	0.5318	14
2006	0.1620	0.2511	0.6078	12
2007	0.2116	0.1989	0.4845	16
2008	0.1604	0.2540	0.6129	11
2009	0.2060	0.2047	0.4985	15
2010	0.3185	0.0941	0.2280	21
2011	0.3370	0.1202	0.2628	20
2012	0.1451	0.2684	0.6491	10
2013	0.1174	0.2852	0.7083	9
2014	0.0658	0.3546	0.8435	5
2015	0.0857	0.3278	0.7928	7
2016	0.0541	0.3579	0.8687	4
2017	0.0496	0.3624	0.8796	3
2018	0.0681	0.3522	0.8379	6
2019	0.0902	0.3325	0.7867	8
2020	0.0432	0.3763	0.8969	2
2021	0.0000	0.4013	1.0000	1

4.3. Analysis of the Horizontal Evaluation Results

The coupling coordination degree is mainly used for the horizontal evaluation of navigation risks. According to the Equations (10)–(12), the results are shown in Tables 4–8, and the visualization results are shown in Figures 5–7. The results show the following: (1) The coupling of two factors presents a weak coupling degree, while the coupling of three and four factors is generally in a strong coupling degree. In two-factor coupling, the coupling degree of E-M is the largest. Moreover, in three-factor coupling, the coupling degree of R-E-M is the largest. These two conditions are the most likely to cause navigation accidents. (2) Referring to the coupling coordination index between risks before 2010, it presents a large value, which represents a high degree of consistency between these risks in the development process and will increase the probability of accidents. After 2010, the degree of consistency between risks gradually decreased, while the risks gradually changed from orderly development to disorderly development, and the navigation became safer. (3) The coupling coordination degree of two factors is smaller than that of three factors. Moreover, the coupling coordination degree of three factors is smaller than that of four factors. (4) The coupling coordination degree related to ship factors is generally small, which indicates that, with the development of science and technology, the impact of scientific and technological risks will be much smaller. (5) Environment factors are important to increase the coupling coordination degree, which indicates that environment factors are still the weak link of autonomous ships'navigation safety in the future. Moreover, it is followed by emergency management factors, shore-based remote control factors and ship factors.

Table 4. The coupling degree B_j of two risk factors.

Year \ Factor	P-R	R-E	E-M	P-E	P-M	R-M
2001	0.3108	0.3967	0.3729	0.2719	0.2922	0.4262
2002	0.3784	0.3944	0.3210	0.3823	0.3080	0.3178
2003	0.3987	0.3141	0.2953	0.4028	0.3748	0.2922
2004	0.3344	0.3117	0.3663	0.3777	0.3929	0.3242
2005	0.3618	0.3266	0.3432	0.3539	0.3803	0.3509
2006	0.3330	0.3006	0.3647	0.3761	0.4041	0.3229

Table 4. *Cont.*

Year \ Factor	P-R	R-E	E-M	P-E	P-M	R-M
2007	0.3783	0.3054	0.3210	0.3701	0.3976	0.3281
2008	0.3295	0.3434	0.3609	0.4297	0.3463	0.2767
2009	0.3540	0.3689	0.3468	0.3097	0.3327	0.3964
2010	0.3530	0.3358	0.3529	0.3640	0.3710	0.3423
2011	0.3902	0.4067	0.3022	0.3117	0.2900	0.3784
2012	0.3549	0.3699	0.3367	0.2835	0.3230	0.4215
2013	0.4075	0.3467	0.2975	0.3758	0.3496	0.3226
2014	0.2353	0.4248	0.4464	0.3255	0.2473	0.3227
2015	0.2668	0.3405	0.4383	0.3691	0.3434	0.3168
2016	0.2732	0.4026	0.4231	0.3085	0.2871	0.3746
2017	0.3255	0.3392	0.3565	0.2600	0.3421	0.4464
2018	0.2398	0.3534	0.4549	0.2708	0.3086	0.4027
2019	0.3466	0.3612	0.3100	0.2260	0.2974	0.4753
2020	0.3172	0.2337	0.3474	0.3583	0.4714	0.3076
2021	0.3365	0.3507	0.3686	0.3801	0.3536	0.3263

Table 5. The coupling degree B_j of three risk factors and four risk factors.

Year \ Factor	P-R-E	R-E-M	P-R-M	P-E-M	P-R-E-M
2001	0.6896	0.7819	0.7137	0.6682	0.9256
2002	0.7634	0.7111	0.6973	0.7007	0.9287
2003	0.7488	0.6473	0.7274	0.7305	0.9253
2004	0.7058	0.6955	0.7188	0.7555	0.9291
2005	0.7133	0.7031	0.7360	0.7292	0.9301
2006	0.6998	0.6894	0.7233	0.7593	0.9285
2007	0.7201	0.6724	0.7422	0.7356	0.9281
2008	0.7436	0.6873	0.6731	0.7576	0.9268
2009	0.7096	0.7450	0.7326	0.6889	0.9292
2010	0.7178	0.7077	0.7239	0.7335	0.9303
2011	0.7458	0.7367	0.7240	0.6484	0.9254
2012	0.7001	0.7535	0.7417	0.6680	0.9270
2013	0.7533	0.6789	0.7321	0.7061	0.9282
2014	0.6992	0.7851	0.6043	0.7156	0.9168
2015	0.6864	0.7420	0.6615	0.7642	0.9255
2016	0.6924	0.7838	0.6675	0.7092	0.9255
2017	0.6608	0.7614	0.7502	0.6780	0.9250
2018	0.6348	0.7905	0.6804	0.7215	0.9212
2019	0.6707	0.7677	0.7574	0.6176	0.9186
2020	0.6570	0.6463	0.7473	0.7782	0.9215
2021	0.7247	0.7149	0.7012	0.7401	0.9300

Table 6. The comprehensive coordination index V_j.

Year	Comprehensive Coordination Index	Year	Comprehensive Coordination Index	Year	Comprehensive Coordination Index
2001	0.0532	2008	0.0516	2015	0.0337
2002	0.0632	2009	0.0583	2016	0.0246
2003	0.0807	2010	0.0874	2017	0.0228
2004	0.0667	2011	0.0827	2018	0.0267
2005	0.0576	2012	0.0434	2019	0.0286
2006	0.0518	2013	0.0407	2020	0.0221
2007	0.0628	2014	0.0265	2021	0.0149

Table 7. The coupling coordination degree K_j of two risk-factors.

Year \ Factor	P-R	R-E	E-M	P-E	P-M	R-M
2001	0.1286	0.1453	0.1409	0.1203	0.1247	0.1247
2002	0.1547	0.1579	0.1425	0.1555	0.1395	0.1395
2003	0.1793	0.1592	0.1543	0.1802	0.1739	0.1739

Table 7. *Cont.*

Year \ Factor	P-R	R-E	E-M	P-E	P-M	R-M
2004	0.1493	0.1442	0.1563	0.1587	0.1619	0.1619
2005	0.1444	0.1372	0.1406	0.1428	0.1480	0.1480
2006	0.1314	0.1248	0.1375	0.1396	0.1447	0.1447
2007	0.1541	0.1384	0.1419	0.1524	0.1580	0.1580
2008	0.1304	0.1331	0.1365	0.1489	0.1337	0.1337
2009	0.1437	0.1467	0.1422	0.1344	0.1393	0.1393
2010	0.1756	0.1713	0.1756	0.1783	0.1800	0.1800
2011	0.1797	0.1834	0.1581	0.1606	0.1549	0.1549
2012	0.1242	0.1268	0.1209	0.1110	0.1185	0.1185
2013	0.1287	0.1188	0.1100	0.1236	0.1193	0.1193
2014	0.0790	0.1061	0.1088	0.0929	0.0809	0.0809
2015	0.0948	0.1071	0.1215	0.1115	0.1076	0.1076
2016	0.0820	0.0996	0.1021	0.0872	0.0841	0.0841
2017	0.0861	0.0879	0.0901	0.0769	0.0882	0.0882
2018	0.0800	0.0972	0.1102	0.0851	0.0908	0.0908
2019	0.0995	0.1016	0.0941	0.0804	0.0922	0.0922
2020	0.0837	0.0718	0.0876	0.0889	0.1020	0.1020
2021	0.0707	0.0722	0.0740	0.0752	0.0725	0.0725

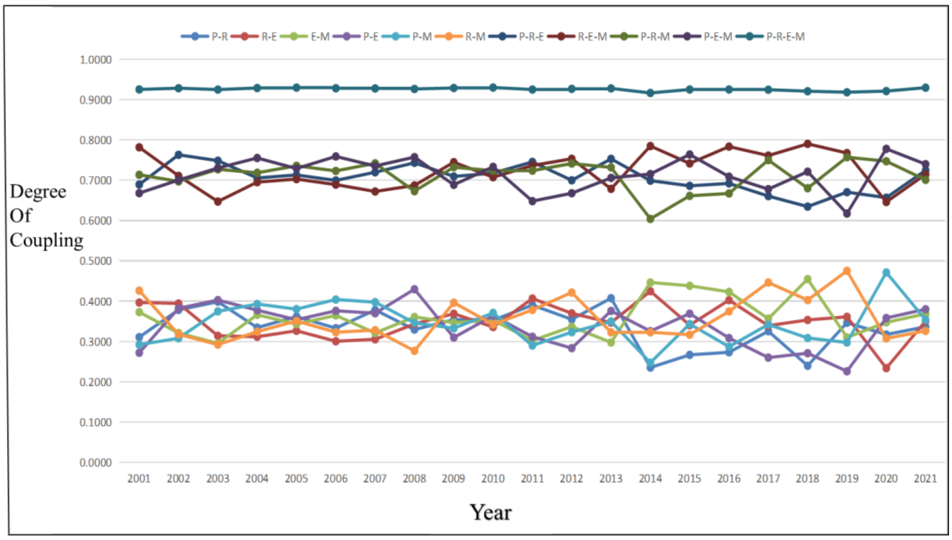

Figure 5. Visualization of coupling degree calculation results.

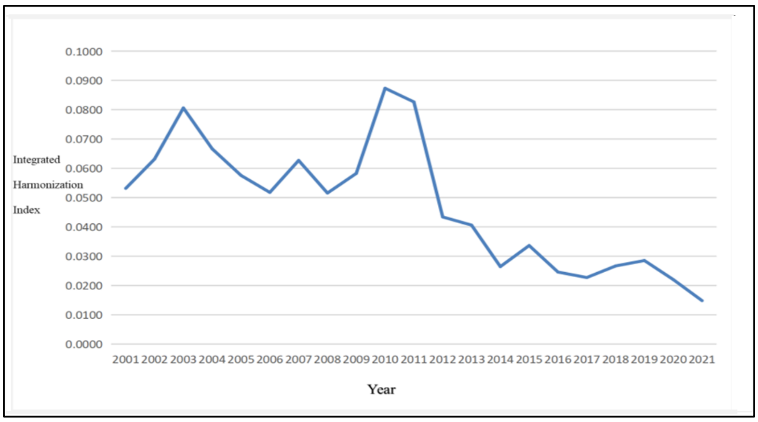

Figure 6. Visualization of comprehensive coordination index calculation results.

Table 8. The coupling coordination degree K_j of three risk factors and four risk factors.

Year \ Factor	P-R-E	R-E-M	P-R-M	P-E-M	P-R-E-M
2001	0.1915	0.2040	0.1949	0.1885	0.2219
2002	0.2197	0.2120	0.2100	0.2105	0.2423
2003	0.2458	0.2285	0.2422	0.2427	0.2732
2004	0.2170	0.2154	0.2190	0.2245	0.2490
2005	0.2028	0.2013	0.2060	0.2050	0.2315
2006	0.1905	0.1890	0.1936	0.1984	0.2194
2007	0.2126	0.2054	0.2158	0.2149	0.2413
2008	0.1959	0.1883	0.1864	0.1977	0.2187
2009	0.2034	0.2084	0.2067	0.2004	0.2328
2010	0.2504	0.2487	0.2515	0.2532	0.2851
2011	0.2484	0.2469	0.2447	0.2316	0.2767
2012	0.1744	0.1809	0.1795	0.1704	0.2007
2013	0.1750	0.1662	0.1726	0.1695	0.1943
2014	0.1361	0.1442	0.1265	0.1377	0.1559
2015	0.1521	0.1581	0.1493	0.1605	0.1766
2016	0.1306	0.1389	0.1282	0.1322	0.1510
2017	0.1227	0.1317	0.1307	0.1242	0.1451
2018	0.1302	0.1453	0.1348	0.1388	0.1569
2019	0.1384	0.1481	0.1471	0.1328	0.1620
2020	0.1204	0.1195	0.1285	0.1311	0.1426
2021	0.1038	0.1031	0.1021	0.1049	0.1176

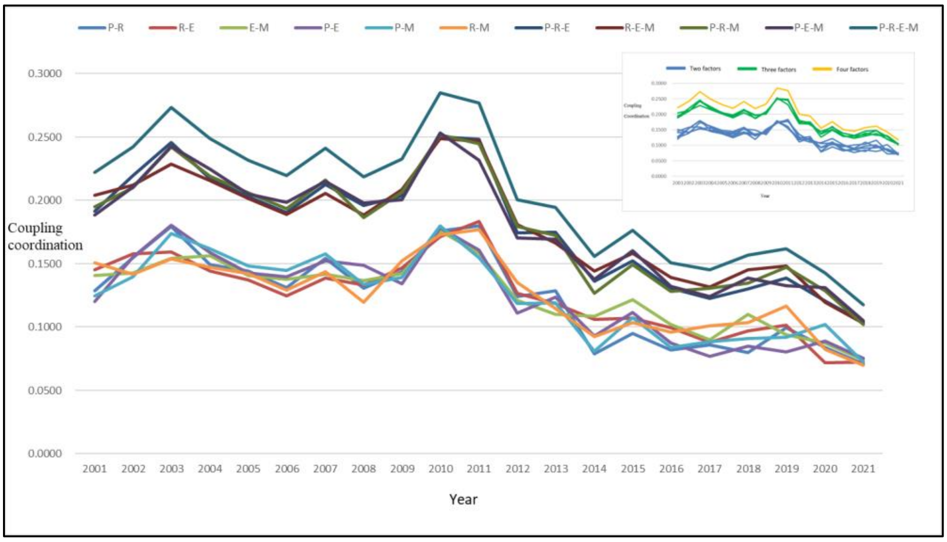

Figure 7. Visualization of coupling coordination degree calculation results.

5. Discussion and Conclusions

A comprehensive risk assessment method for autonomous ship navigation based on an Entropy–TOPSIS–Coupling coordination model is proposed in this paper. The coupling of two factors presents a weak coupling degree, while the coupling of three and four factors generally generates a strong coupling degree. The two cases of E-M and R-E-M are the most likely to produce accidents under the coupling conditions of various multi-risk factors. The coupling coordination degree of two factors is smaller than that of three factors. Moreover, the coupling coordination degree of three factors is smaller than that of four factors, which conforms to the general law of the development of things. The coupling coordination degree related to ship factors is generally small, which indicates that, with the development of science and technology, the impact of scientific and technological risks will be smaller and smaller.

However, this paper still has some shortcomings and further research needs to be conducted. With the use of historical accident statistics of traditional manned ships to simulate autonomous ships, the evaluation results may not always conform with the actual situation. Further research should be mounted to verify the applicability of the presented method in specific actual scenarios. With a large number of sea trial data, the development of autonomous ships will gradually mature and form a high-quality autonomous shipping system.

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