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Research in marine accidents: A bibliometric analysis, systematic review and future directions

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ABSTRACT

In order to analyse the research evolution and knowledge frontier in the research of marine accidents, 491 literatures on marine accidents in the Web of Science database from 2000 to 2022 are taken as data sources. Integrated with literature analysis of traditional method, CiteSpace and VOSviewer are then jointly used for the development of the knowledge network map and cluster analysis, and the knowledge of network map, research hotpots, research evolution and knowledge frontiers is obtained. It is found that there is a close cooperative relationship among journals, researchers, research institutions and countries or regions. According to the subjects and methods, the study of marine accidents can be divided into two parts: the analysis of the influential factors and accident consequences, as well as the methodology development of traditional and emerging technology. In this context, the analysis of human factors in remote-controlled ships, the prevention of accidents in Arctic waters have become research hotspots, while emerging accident analysis methods such as machine learning and big data mining also have shown powerful insights in the analysis of marine accidents. In terms of innovation, the bibliometric approach enhances the ability to handle large literature databases and conduct network analysis. Moreover, this study visualises collaborative networks, analyses evolution trends, reveals the research hotpots, and conducts a comparison and discussion of mainstream approaches in marine accident research. As a result, this study provides a theoretical basis and implementation direction for the development of maritime safety.

1. Introduction

While the shipping industry has brought efficiency, speed and convenience to the global flow of goods, it has also inevitably resulted in various marine accidents (Mansyur et al., 2021; Wang et al., 2023a). Once a marine accident occurs, it will normally generate a serious impact on the safety of life, property and the environment (Wang et al., 2022c). In recent decades, the study of marine accidents has been one of the hot topics closely given the fast growth of the shipping industry (Rawson and Brito, 2022; Wang et al., 2022b). The International Maritime Organization (IMO), national maritime authorities, shipping companies and other stakeholders have put significant efforts to improve maritime safety, but the number of marine accidents is still large (Cao et al., 2023). For example, in its annual accident statistics, the European Maritime Safety Agency stated that 22,532 water traffic accidents occurred between 2014 and 2020 (European Maritime Safety Agency, 2021). The annual report published by Allianz Global Corporate & Specialty Risks in 2022 suggested that although the number of ship losses in 2021 was 57% lower than a decade earlier, there was the occurrence of 3000 ship accidents in the year (Allianz Global Corporate and Specialty, 2022).

At present, the world's maritime safety status is still challenging due to various uncertainties including but not limited to new technologies (e.g., autonomous ships), climate change, and economic upheavals (Aydin

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et al., 2021). In order to better understand, analyse the cause mechanism of accidents and improve the overall level of maritime safety, researchers have studied different aspects of marine accidents, such as influential factors and spatial distribution (Acharya et al., 2017; Wang et al., 2022a). Acharya et al. (2017) analysed the spatial distribution of marine accidents occurring in the waters around the relevant East Asian countries, which provided new insights for accident prediction, management and decision making in waters with high accident rates. Navas de Maya and Kurt (2020) used Fuzzy Cognitive Maps and expert knowledge to extract the influential factors of the occurrence of marine accidents. It was found that the main factors influencing accidents on bulk carriers were insensitivity of the pilot to the pre-accident situational awareness and inadequate communication. Simultaneously, different methodologies have been used to investigate marine accidents, and useful results have been achieved. For example, a combination of Fault Tree Analysis (FTA), Grounded Theory (GT) and Bayesian Network (BN) was used by Wang et al. (2021b). It was found that the key factors in mitigating the consequences of a ship fire were an effective ventilation system and rapid emergency response by crew and passengers. Fan et al. (2020b) analysed the influential factors of marine accidents by a data-driven method, and identified the five key factors affecting safe ship navigation. Ventikos et al. (2017) analysed accidents in the waters around the Aegean Sea over a 10-year period, discussed two models to differentiate the results. In addition to those attempts, researchers have used ordered logistic regression (Mansyur et al., 2021; Weng et al., 2016, 2018, 2019; Yip, 2008), Human Factors Analysis and Classification System (HFACS) (Adumene et al., 2022; Aydin et al., 2022; He et al., 2022; Kandemir and Celik, 2021; Kaptan et al., 2021; Sarıalioğlu et al., 2020; Yildiz et al., 2021; Zhang et al., 2019), machine learning (Atak and Arslanoğlu, 2022; Filom et al., 2022; Hou et al., 2022; Paltrinieri et al., 2019; Rawson and Brito, 2022; Uyanık et al., 2021; Zhang et al., 2022a) and other methods to improve the research on marine accidents in recent years. These achievements provide more perspectives for the prevention of marine accidents, which also bring guidance and assistance for the management of relevant maritime agencies.

The above-mentioned literatures focus on different research areas and various research methodologies of marine accidents. Meanwhile, some review literatures summarise the results of research in this field. The review and summary of marine accident research is not only helpful to understand the overall trend of marine accident research, but also can provide new ideas on accident prevention and future research direction of maritime safety. Luo and Shin (2019) reviewed relevant marine accidents literatures over the past 50 years and found that the focus of research in the field of marine accidents has gradually shifted from marine engineering to human factors. Goerlandt and Montewka (2015) refined the definition of ship risk analysis based on the influential factors in marine accidents and suggested that different risk assessment methods can obtain different results. In fact, various factors such as human, ship, the environment and management cause marine accidents often in a collective and joint manner, and the potential severity of an accident also varies (Uğurlu et al., 2022; Wang et al., 2023b). It is difficult to provide an overview of the overall study of marine accidents through a conventional review due to the large number of research papers and comprehensive features of accidents. Therefore, it is necessary to collate the hotpots and the research related to marine accidents through emerging technologies. Further, the previous studies in this area fail to investigate the evolution of the marine accidents and the two subsets: influential factors and severity of the consequence.

With the fast growth of scientometrics and bibliometric techniques in recent decades, scientometric analysis and information visualisation techniques have been widely used in literature reviews and some achievements have been made (Fu et al., 2021; Kandemir and Celik, 2022; Li et al., 2021b). For example, Jiao et al. (2021) used CiteSpace and VOSviewer to conduct a knowledge network mapping analysis of safety issues in Liquefied Natural Gas (LNG) transportation. Based on a LNG literature database, the research priorities and research trends at different stages were summarised and discussed. Fu et al. (2021) used VOSviewer as the bibliometric methods, discussed the relevant factors affecting the safety of the Arctic shipping route by analysing 221 retrieved literatures. Those studies showed that the bibliometric analysis tools, CiteSpace and VOSviewer have good applicability in the literature review and analysis. Among them, CiteSpace is an information visualisation software tool written by Chen (2006) using JAVA language. VOSviewer is a scientific knowledge mapping analysis software tool written by van Eck and Waltman (2010). In view of these advantages, the bibliometric approach is able to enhance this study in the following two aspects: a) Comparing to conventional review analysis methods, the bibliometric approach enables the review of a larger literature database, generates more comprehensive analysis results, which meets the need of this study to systematically analyse the research network and identify research hotspots and knowledge frontiers; b) Combining with conventional qualitative review analysis method, the bibliometric method improves the reliability and informativeness of the current level of review research, provides a more intuitive presentation and articulation of the future direction of marine accident studies. Therefore, by combining bibliometrics with traditional literature analysis methods, the research focus and research context in the field of marine accidents are analysed holistically. Within this context, the novelties/innovations of this study are as follows:

1) In terms of the research methodology, distinguished from previous studies, CiteSpace and VOSviewer are newly used in this study as a new information visualisation tool to analyse 491 marine accident-related literature work. As a result, it enhances the ability of review-based studies in processing large literature databases and conducting network analysis in a comprehensive and systematic way.
2) With a very specific definition of the new research scope on marine accidents in the past two decades (which is at large overlooked in the current literature), this study not only identifies and analyses relevant topics in the field of marine accident research, but also visualises the obscure elements such as cooperation networks and evolution trends, hence generating new implications.
3) By the new in-depth analysis of the evolution pattern, this study makes new contributions to maritime safety on: the identification of the hotspots of the research topics along with different timeframes in the past two decades; the development of the coordination between accidents, influential factors and countermeasures (e.g., regulations).
4) The advantages and disadvantages of the mainstream methods used for marine accident analysis are also analysed for the first time, and the insights on how to best develop and promote marine accident studies for ensuring safety at sea are therefore obtained.

The contents of this study are shown below: the second part presents the sources and collection process of the relevant literatures, as well as the survey methodology used in this study; the third part discusses and analyses the collaborative network of journals, researchers and nations/regions and institutions respectively; the fourth part summarises and analyses the research subjects and the research methodology in the field of marine accidents; the fifth part discusses the new findings including a comparative analysis with the previous review works in the literature for highlighting its new contributions and the recommendation of the future research directions; the sixth part summarises the whole study.

2. Data and methods

2.1. Data sources

To promote the reliability of the research data, Web of Science (WOS) compiled by the Institute for Scientific Information (ISI) is used as the primary source for the literature search. It covers more than

12,000 high-impact journals and is considered to be the most comprehensive literature database in the world (Jiao et al., 2021).

In this study, Science Citation Index (SCI) and Social Sciences Citation Index (SSCI) are selected as the citation databases for the literature search, with the search string set to "maritime accident*" or "marine accident*" or "ship* accident*" or "water transport* accident*". The symbol "*" indicates other forms of a word, e.g., "accident" and "accidents", "ship" and "ships" and "shipping". In addition, to focus on the discipline of marine transportation, this study chooses "maritime", "marine", "ship*" and "water transport*" as the target research area. Then, to ensure in-depth research, this study will focus primarily on marine accident-related research. While there are some similarities between marine accidents studies and maritime safety studies, the subject of maritime safety and risk assessment has a broader coverage. The study of marine accidents can be treated as a subset of the topic of maritime safety and risk assessment to some extent. Therefore, the term "accident*" is chosen as the main research topic for this study to ensure the correlation with marine accidents. In order to reflect the recent research progress, the time period for the search is set from "2000-01-01 TO 2022-08-31". The language of the literature search is set to "English". After completing the relevant search settings, the initial 607 papers are obtained.

Subsequently, irrelevant papers are removed using manual screening based on the 607 retrieved papers. For example, in some papers, marine accidents only appear in the background section, where those studies focus on analysing the effects of marine pollution on marine organisms and the ecology, and in others, where the medical field is concerned with diseases of marine organisms. After screening out the irrelevant papers, 491 papers related to marine accidents are obtained and used to support the follow-up study. The number of papers is counted by year, as shown in Fig. 1.

It can be concluded from Fig. 1, the number of papers on marine accidents was low between 2000 and 2007. Although 2008–2016 saw a slight climb, the number of papers still fluctuated in a low range. After 2016, the number of papers on marine accidents started to increase consistently and reached a peak of 89 papers in 2021. This shows that research in the field of marine accidents has received more attention in recent years and that the growth trend will continue.

2.2. Research methodology

Based on the established literature database, the study is conducted in three stages: visual analysis, literature analysis and discussion, as shown in Fig. 2.

At the visual analysis stage, these papers are visualised using CiteSpace and VOSviewer as bibliometric analysis tools, depending on the specific subject and topic of the study. The visualisation results are then analysed and relevant conclusions are drawn. For example, when

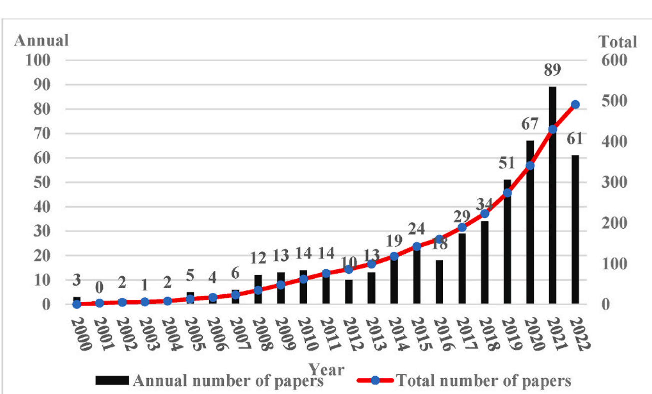

Fig. 1. Results of literature statistics for the period 2000–2022.

analysing the focus of marine accident research, CiteSpace can use keywords, abstracts, terms to obtain clusters of research topics, while VOSviewer can divide ranges by colour to generate knowledge maps. In fact, CiteSpace and VOSviewer have their individual advantages as bibliometric analysis tools for knowledge mapping and visualisation. CiteSpace creates maps in a variety of colour styles that can be adapted to suit preferences. The co-occurrence map generated by CiteSpace can be used to analyse the focus and relevance in marine accident studies (Chen, 2006). The visual mapping networks built by CiteSpace contain centrality metrics that can provide a reliability method for finding key points between different specialisms or central points in an evolutionary network (Li et al., 2021b). Progressive Pathfinder network scaling can also be used to determine whether a particular link is retained. VOSviewer, on the other hand, is relatively easier to use, and enables clear analysis of authors, countries and inter-institutional collaboration networks, hence helping to obtain the current state of research collaboration in the field of marine accident research (van Eck and Waltman, 2010).

Based on the quantitative analysis and visualisation of the selected literatures using CiteSpace and VOSviewer, this study also combines traditional literature analysis methods to examine the visualisation results, completes a review study of the different directions in the field of marine accident research. It therefore makes increased methodological contributions on how to combine classical and emerging literature review methods for generating systematic new findings.

3. The overall analysis of research network

3.1. The co-citation network analysis of published journals

After the data screening, 491 papers are put into VOSviewer and the data is read and parsed. The analysis results reveal that the 491 papers are from 124 journals. The different topics of these journals indicate that there is a wide range of journals on topics related to marine accidents. The journal co-citation network in the field of marine accidents is shown in Fig. 3. The seven journals published the most papers are shown in Table 1.

The size of the nodes in Fig. 3 indicates the number of papers related to marine accidents published in corresponding journal, the thickness of the connecting lines indicates the closeness of the links between the journals, and the colour of the nodes and lines represents the similarity of the journal topics. Overall, there is a strong link between the various journals around the world. This linkage is mainly reflected in the similarity of the topics of the papers published and the co-citation of journals. For example, *Safety Science* and *Accident Analysis and Prevention* focus on scientific and technical research related to accidental injury and damage, occupational safety. *Ocean Engineering* focuses on the research and work related to the field of vessel operation and design, marine environmental protection. *Maritime Policy & Management* and *Transport Policy* have a higher profile in the areas of maritime policy and management practices.

An analysis of Table 1 shows that the number of papers published in each of the 7 listed journals is greater than 10. This indicates that the above 7 journals are more focused on research in the field of marine accidents and have more concentrated research topics. *Ocean Engineering, Journal of Marine Science and Engineering* and *Safety Science* all contain more than 40 papers. *Safety Science, Marine Engineering, Reliability Engineering & Systems Safety* and *Accident Analysis & Prevention* all have more than 1000 citations. *Safety Science* and *Ocean Engineering* are the two most important journals in the field of marine accident research, taking into account both the number of papers published and the number of citations. The reason for this may be that most papers related to marine accidents are published in journals in the fields of vessel operation, and occupational safety.

In order to demonstrate the more obvious impact of each journal in the research field of marine accident, this study introduces a new value

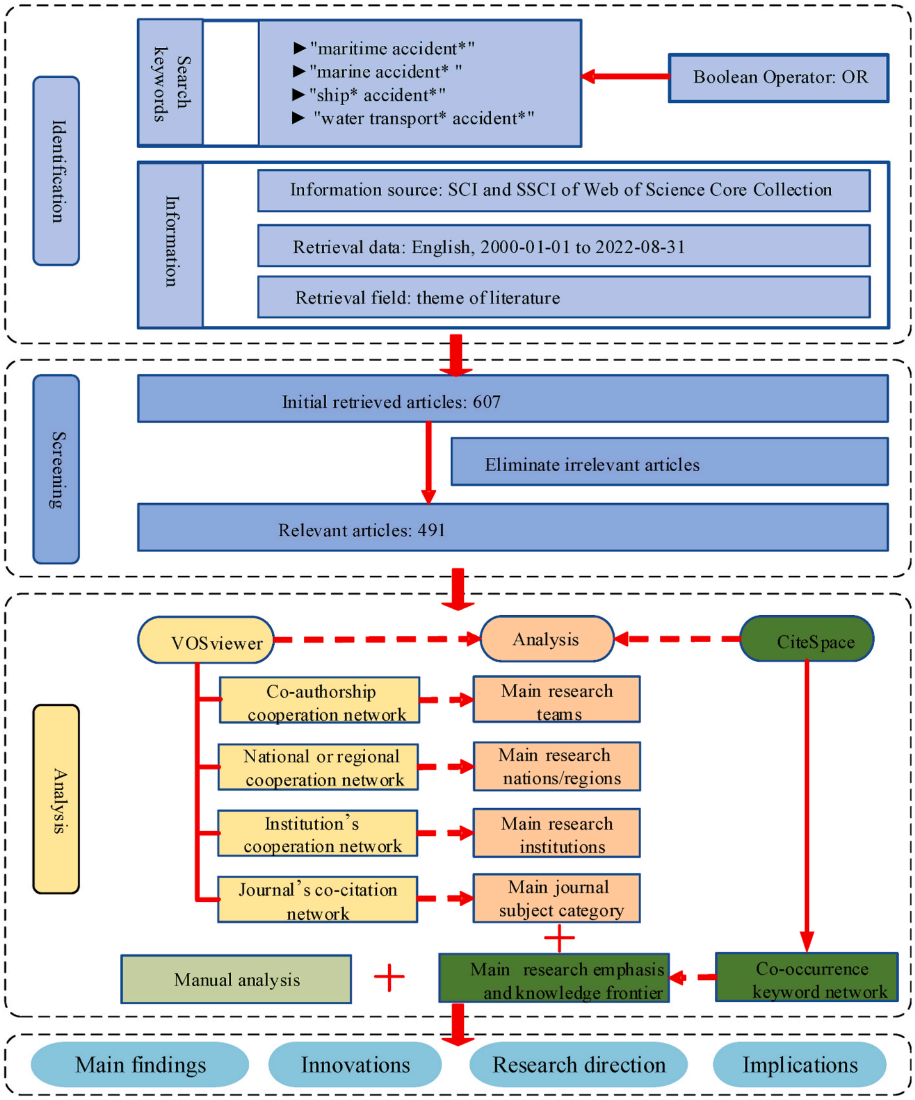

Fig. 2. The research framework.

called citations per publication. Table 1 shows that the citations per publication in *Accident Analysis and Prevention, Safety Science, Reliability Engineering & System Safety* all exceed 40, and most of the journals in Table 1 have an average citation value of over 20, further confirming the high impact of these journals in the research field of marine accident.

3.2. The analysis of Co-authorship network

An analysis of the co-authorship of the 491 papers can reveal the collaboration situation of global researchers. In this study, VOSviewer is used to map the co-authorship network between authors to obtain a visual network of collaborative authors in the field of marine accidents. The size of the nodes indicates the number of papers published by the authors, the thickness of the connecting lines indicates the closeness of the connection between the authors, and the colour of the nodes and lines represents the cooperative relationship between the authors, as shown in Fig. 4.

Comparing the network of co-authorship internally in Fig. 4, different research focuses of different research teams can be obtained. For example, Wang's team from Liverpool John Moores University (LJMU) has carried out extensive cooperation with Ugurlu's team from Ordu University in terms of the number of papers. The team of Kujala, Goerlandt and Montewka from Aalto University has also done some outstanding research in the field of marine accidents. The LJMU team (by Wang and Yang) has shown a wide range of research links/collaborations with the other leading teams in the area, including the ones led by Yan (Wuhan University of Technology), Liu (Dalian Maritime University), Celik (Istanbul Technical University), Chen (Shenzhen University) and Wang (Shanghai Maritime University).

3.3. The network analysis of countries/regions and institution

Table 2 shows the five countries or regions with the highest number of the publications and the number of citations of their respective papers. Fig. 5 shows the visual network of cooperation between countries or regions in the field of marine accidents. The size of the nodes indicates the number of publications of the country or region, and the thickness of the lines between the nodes indicates the degree of cooperation between countries or regions. It can be seen from Table 2 that China has outstanding contributions in the field of marine accident research, ranking first with 147 publications, followed by Turkey (66), South Korea (57) and the UK (50). Combined with the inter-country or inter-regional cooperation network in Fig. 5, it can be seen that most of the countries or regions studying marine accidents are located in the coastal regions of East Asia or Europe, where the shipping industry is developed with priority.

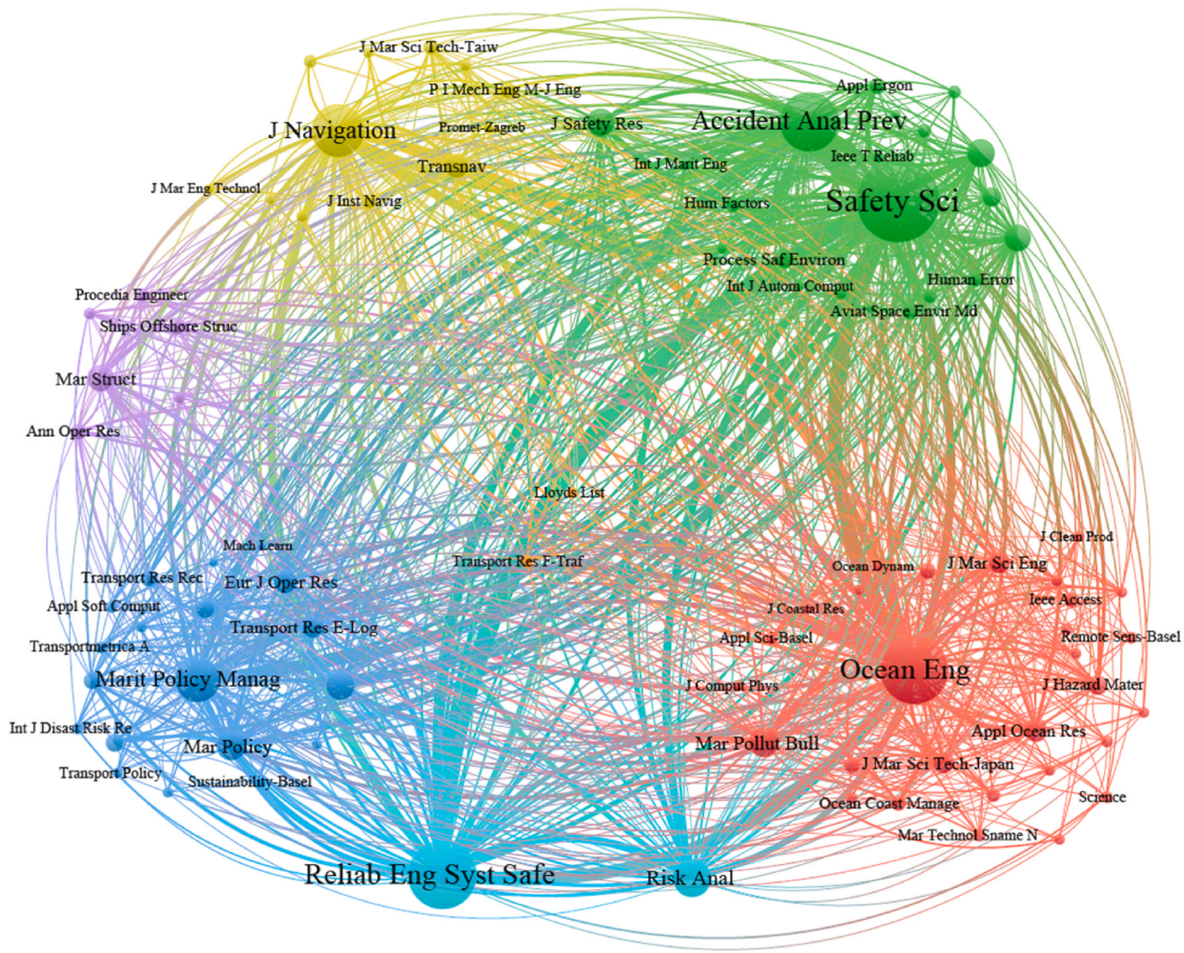

Fig. 3. The journal co-citation network in the field of marine accidents.

Table 1
Top 7 journals publishing papers related to marine accidents.

No.	Source	Documents	Citations	Citation per publication	Subject category[a]
1	Ocean Engineering	65	1290	20	Engineering; Oceanography
2	Journal of Marine Science and Engineering	40	154	4	Engineering; Oceanography
3	Safety Science	40	1971	49	Engineering; Operations research & Management science
4	Maritime Policy & Management	24	452	19	Transportation
5	Journal of Navigation	22	594	27	Engineering; Oceanography
6	Reliability Engineering & System Safety	22	1027	47	Engineering; Operations research & Management science
7	Accident Analysis and Prevention	13	1175	90	Transportation; Public, Environmental & Occupational health; Social science, Interdisciplinary; ergonomics

[a] Subject category of different journals is retrieved from the 2019 edition of Journal Citation Reports.

Fig. 6 shows a visual network of institutional collaboration in the field of marine accidents. The size of the nodes indicates the number of papers published by the institution, the thickness of the connecting lines indicates the strength of the links between the institutions, and the colour of the nodes and lines indicates the collaboration between the institutions. Fig. 6 shows that the ten institutions with the highest number of publications are Wuhan University of Technology (45), Shanghai Maritime University (33), Liverpool John Moores University (31), Istanbul Technical University (28), Dalian Maritime University (25), Aalto University (21), Karadeniz Technology University (21), Hong Kong Polytechnic University (15), Delft University of Technology (13), and Korea Maritime & Ocean University (13). In addition, Ordo University, Mokpo National Maritime University, National Taiwan Ocean University have also made significant contributions to the field of marine accident research.

From the analysis of each institution as a whole, it can be found that the geographical location of the institution and the development of the discipline are directly related to the degree of research. In terms of geographical location, most of the institutions are located in port cities. For example, Shanghai and Wuhan are the core cities of the Economic Belt of Yangtze River and are important integrated water transportation hub in China; Istanbul is the largest city in Turkey and is located at the entrance to the Black Sea, making it an important maritime city across Europe and Asia. In terms of disciplinary development, the study of marine accidents is an important part of the field of marine transport or maritime engineering. For example, all those universities are the most

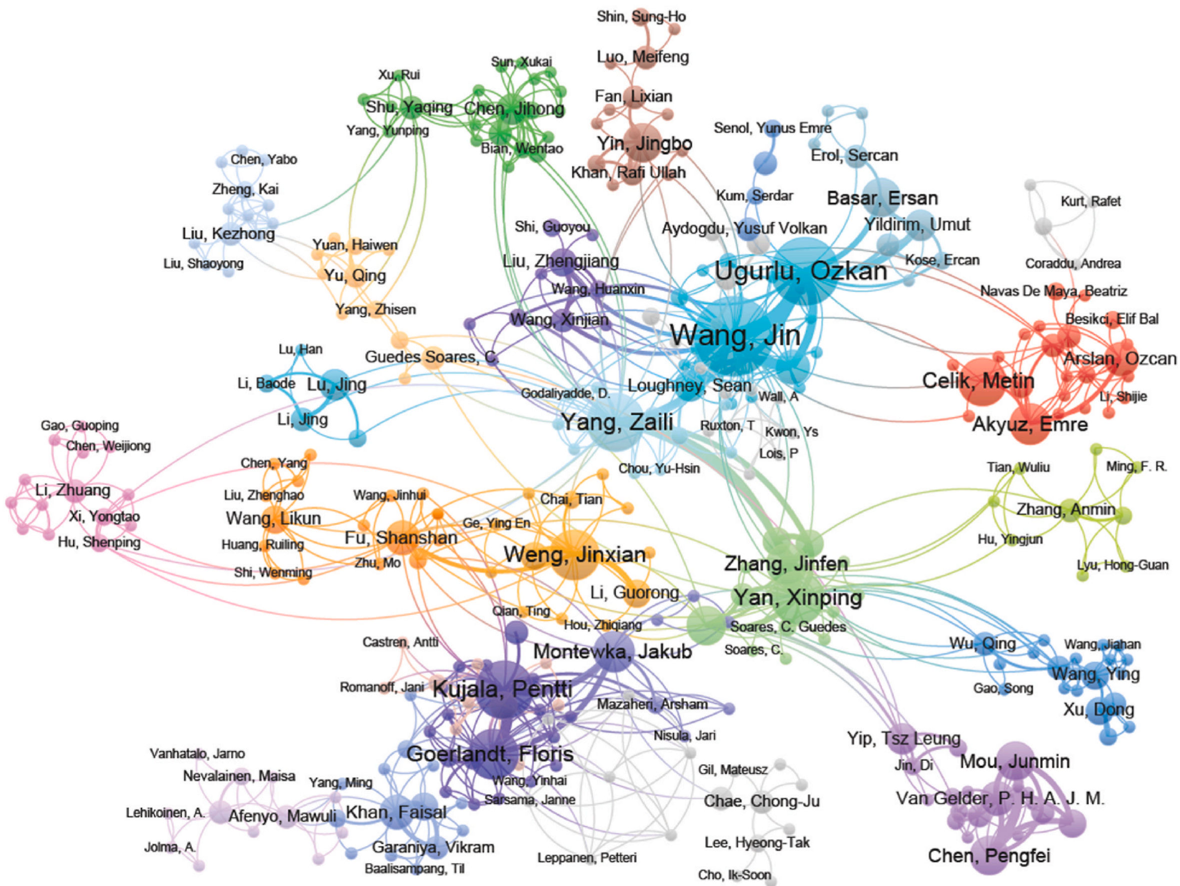

Fig. 4. Authors cooperation network in the field of marine accidents.

Table 2
Top 5 Countries/regions with the highest number of papers related to marine accidents.

Country	Documents	Citations
Peoples R China	147	2137
Turkey	66	1504
South Korea	57	544
England	50	1531
Finland	26	1429

leading institutions of marine transport or maritime engineering, which include research on marine accidents.

4. Research hotspots and knowledge frontiers

CiteSpace is able to identify and extract relevant topics. It also presents the highly cited papers in each topic in chronological order, resulting in a clustering timeline graph. Considering the issue of relevance, this study uses keywords for the clustering analysis of research topics. This is because the keywords of papers can show the representative of the topic studied in the paper. Also, considering the issue of timeliness and comprehensiveness, this study retraces the citations of relevant papers over the past 22 years. To avoid causing omissions in the screening process, this study sets the cited literature selection threshold to 100% to include all cited literature, as shown in Fig. 7. The generated clustering labels represent the corresponding research topics, the nodes in each timeline represent different keywords under the topic, and the highly cited keywords in each clustering label represent the key content in the topic.

In Fig. 7, "#0 HFACS" is the largest knowledge area, containing 74 papers, and the average publication year of these papers was 2015. It is worth noting that CiteSpace will count some papers repeatedly, mainly because these studies may be related to the above clusters at the same time. For example, some studies used AIS data as the main data source for accident research on ship collision avoidance, then these papers may be counted by clusters "#1 AIS data" and "#3 Intelligent collision avoidance" at the same time. Similarly, some papers mainly use the method of the HFACS to analyse and summarise human error in marine accidents. These papers may be cited multiple times in the cluster tags "#0 HFACS" and "#5 Human factor", e.g., these references (Celik and Cebi, 2009; Chauvin et al., 2013; Qiao et al., 2020a). However, some of the highly cited papers in the "#5 Human factor" cluster also used other methods to analyse the impact of human factors in marine accidents, which differed from the focus of "#0 HFACS". The former focuses more on the content of the study, while the latter emphasises more on the methodology. Therefore, this study suggests that this method of repeated classification is valid. To check the reliability of the CiteSpace classification, the papers that have been classified multiple times will be reclassified in this study after manual inspection, and the results can be shown in Table 3.

According to the occurrence frequency and the year of keywords, the evolution trend of the research field of marine accidents can be obtained. Fig. 8 illustrates the evolution of marine accident research. At the beginning of the 21st century, there was a widespread interest in methods for assessing maritime risks. The risk models and validation methods associated with marine accidents have also been used to some extent. At the same time, the environmental problems caused by marine accidents were gradually noticed, probably in connection with the increased environmental awareness of the shipping industry. Subsequently, the investigation and study of marine accidents or accident reports continued to be the focus of attention in the field of marine

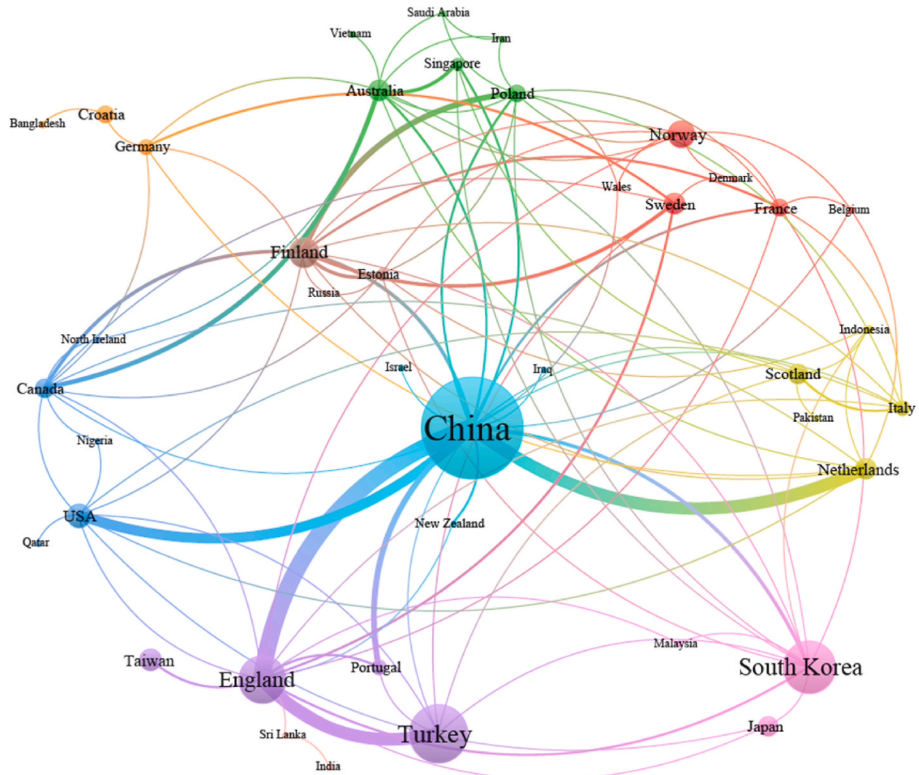

Fig. 5. National or inter-regional cooperation network in the field of marine accidents.

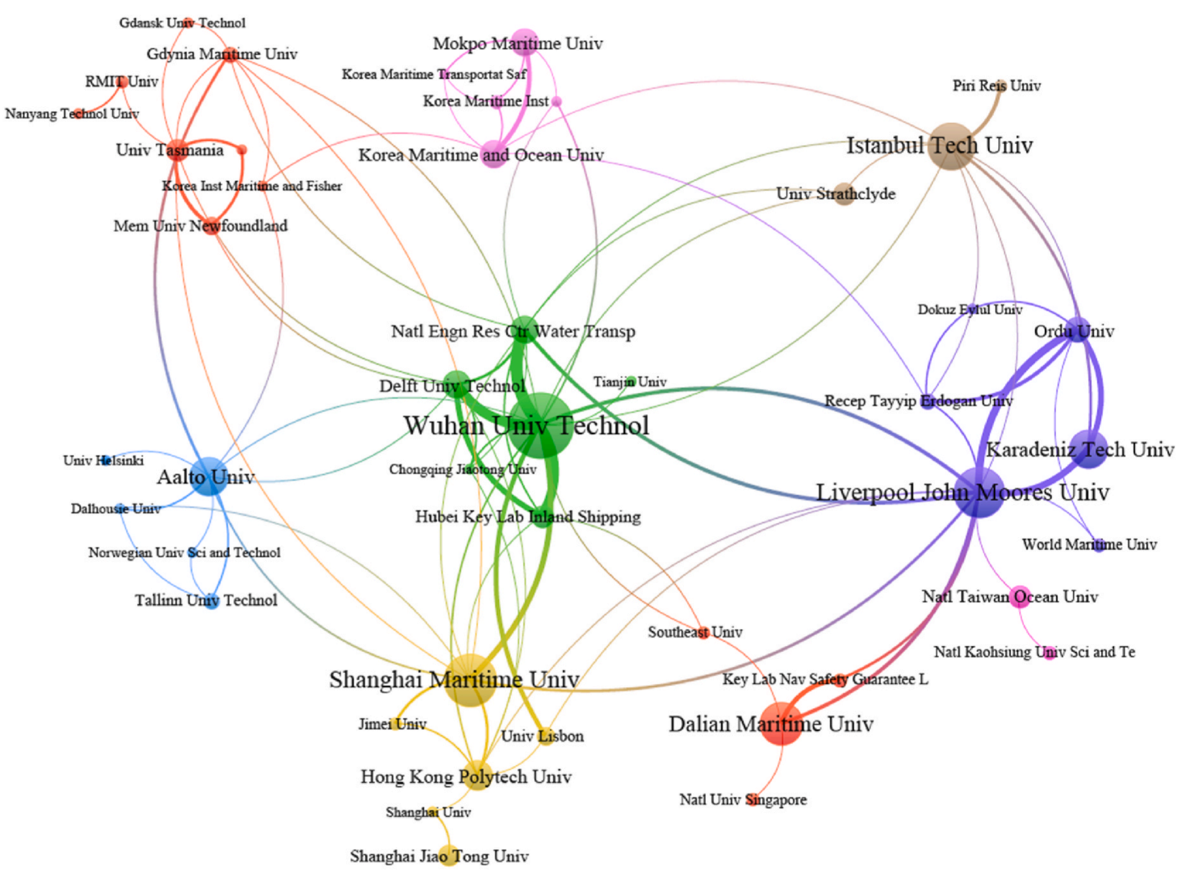

Fig. 6. Global institutions cooperation network in the field of marine accidents.

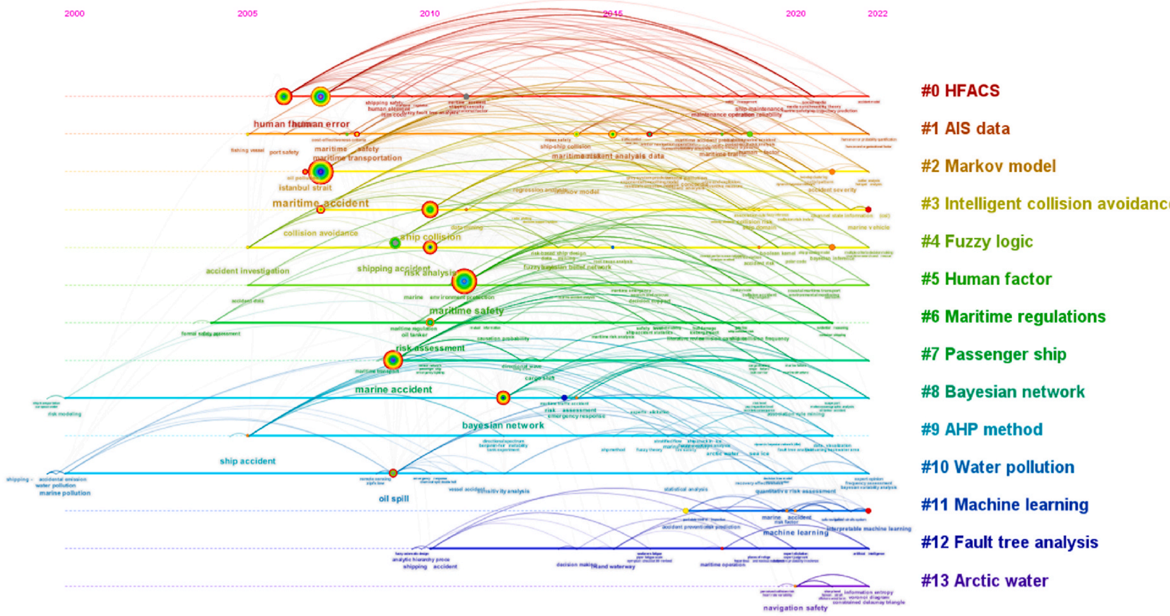

Fig. 7. The timeline result of keywords on marine accident after clustering.

Table 3
Statistics on clustering results.

No	Size	Name	Mean (Year)
0	74	HFACS	2015
1	73	AIS data	2016
2	73	Markov model	2017
3	61	Intelligent collision avoidance	2019
4	60	Fuzzy logic	2017
5	52	Human factor	2017
6	49	Maritime regulations	2015
7	49	Passenger ship	2016
8	48	Bayesian network	2016
9	47	AHP method	2016
10	43	Water pollution	2012
11	34	Machine learning	2020
12	26	Fault tree analysis	2016
13	19	Arctic waters	2021

accidents, and researchers began to focus on the impact of human factors on marine accidents. Environmental issues also became a key focus of marine accident analysis, as the environmental hazards of fuel spills from accidents have also received more attention.

Since 2008, the human factor in marine accidents has become increasingly important and been considered to be a key factor in the occurrence and consequences of marine accidents. Since 2013, the scope of marine accident research has been expanded, such as inland waterway accidents. Moreover, AIS data was widely used as a data source for marine accident data analysis (Zhang et al., 2021a). Simultaneously, more analytical methods have been applied, such as HFACS, AHP methods, FTA and expert knowledge.

In the latest research, computer technology has developed rapidly in the field of marine accident research. Firstly, machine learning methods combined with big data have become an important technical tool in the marine accident research process. The process of intelligent ships has also become one of the future directions of the shipping industry, and the prospective assessment and analysis of intelligent ships has become an important part of the research into the prevention of marine accidents. In addition, climate change has raised concerns about Arctic shipping routes. Navigational risk assessment and accident prevention in Arctic waters is one of the key areas for future research. In addition, the environmental issue in Arctic waters has always been considered as a hot topic of interest in recent years.

In general, the research evolution of marine accidents has taken place in two main aspects: the subject and the methodology of marine accidents analysis. In fact, this is in line with the development of scientific research, in which research methods and research content contribute to each other's development. In recent years, there have been developments in the analysis of the consequences of marine accidents, mainly in terms of casualties, damage to ships and environmental impact. Furthermore, there has been a marked change in the methodology of marine accident studies. Therefore, this study focuses on two aspects: the subjects and the methodology, in order to analyse the research hotspots and knowledge frontiers of marine accidents.

4.1. *Subjects of marine accidents analysis*

In this section, the subjects of analysis are further divided into influential factors and consequences of accidents, in accordance with the clustering labels studied.

4.1.1. *Influential factors of marine accidents analysis*

In this section, the research of the accident influential factors is discussed further. Through a systematic analysis of the relevant literature, the accident influential factors are further divided into five categories (human, ship, environment, management, and accident) (Fan et al., 2020a; Wang et al., 2021a; Wu et al., 2022), the specific quantitative clusters are shown in Table 4, and the specific components of the classification are given as follows:

Human factors: They are also known as human error. In human reliability analysis, human factors mainly include operational errors or violations, communication problems between crew, ship and shore-based equipment, experience or knowledge errors caused by poor expertise due to short years of service or time on the rank, fatigue problems due to poor physical or mental conditions of the crew (Akyuz and Celik, 2018; Chauvin, 2011; Cui et al., 2022; Fan et al., 2020b; Kandemir and Celik, 2022).

Ship factors: Ship factors mainly contain ship particulars and voyage statement. Specifically, ship particulars include factors such as ship type, age, tonnage and engine power. Voyage statement includes the validity of the ship and crew certificates, the seaworthiness of the cargo and the compliance with PSC inspections (Öztürk et al., 2021; Renner and

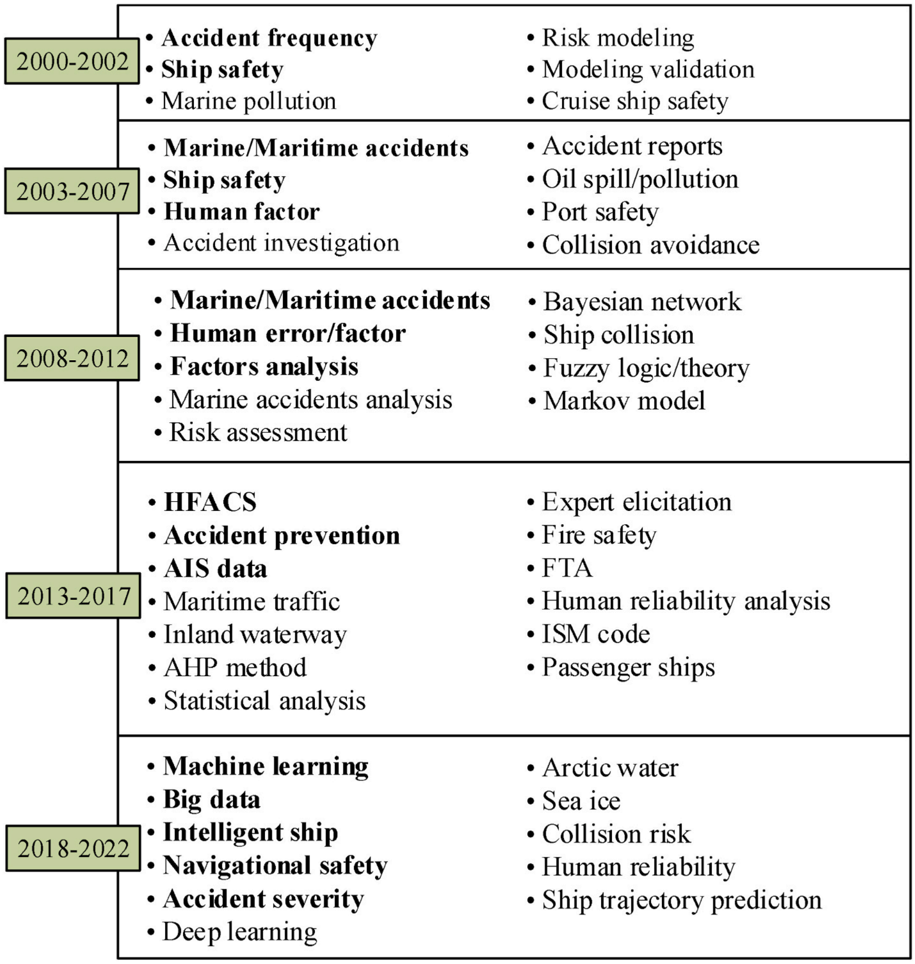

Fig. 8. Evolution of marine accidents research.

Kuletz, 2015; Wang et al., 2022b; Weng et al., 2019).

Environmental factors: Environmental factors contain the external and the navigational environment. External environment includes the location of the accident, visibility, wind and current conditions. The navigational environment includes conditions such as the scale and navigational density of the channel (Häkkinen and Posti, 2014; Jon et al., 2021; Liu et al., 2020; Öztürk et al., 2021; Yildiz et al., 2022; Zhang et al., 2021c).

Management factors: The stakeholders of management factors are administration, ship company and the ship management factors. Administration factors mainly include the adequacy of regulations and supervision. The ship company factors mainly include the soundness of the safety management system of ship companies, the timeliness of correcting problems and the corporate safety culture. Ship management factors mainly include the effectiveness of drills and training (Arslan and Turan, 2009; Hänninen et al., 2014; Lan et al., 2022; Zhang et al., 2022b).

Accident factors: Accident factors mainly include the type and the time of the accident (Cao et al., 2023; Chen et al., 2019; Fan et al., 2020b, 2020c; Jon et al., 2021; Weng et al., 2016; Yildiz et al., 2022).

Many studies focused on the impact of human factors on marine accidents, which often included factors such as unsafe behaviour, fatigue, skills and communication (Lan et al., 2022). Celik and Cebi (2009) used HFACS as a method to identify human errors in marine accidents, in which the HFACS method was enhanced based on a fuzzy analytical hierarchy process to increase its data handling capabilities. It was concluded that unsafe acts, cooperation, communication, planning were given higher weights in human errors. Combined accident analysis models, Akyuz (2017) used an analytical network process method with HFACS to investigate human error in LNG spills. The study suggested that unsafe acts in human error had the highest priority among all accident factors.

In recent research, much attention has been paid to projects related to Maritime Autonomous Surface Ships (MASS), whose main aim is to enable ships to operate with varying degrees of independence from humans, which on the one hand can reduce the probability of marine accidents due to human error of the ship's operators. However, on the other hand, the initial MASS navigation may require remote control by shore-based personnel, which again can lead to a new kind of human errors (Zhang et al., 2020). Wróbel et al. (2021) used an expert knowledge approach to evaluation the navigational risks of MASS, and found that condition of operator and failure to correct known problems were the most important human factors affecting the remote-control process. Liu et al. (2022) and Yoshida et al. (2021) specifically analysed the impact of human factors associated with the remote operator. It was found that fatigue, lack of training, and lack of communication were the main factors contributing to operator errors.

Based on the identification and analysis of human factors, the researchers further proposed the management factors, and analysed them in three main areas: ships, companies and the maritime administration (Aydin et al., 2021, 2022). Grabowski et al. (2009) argued that different marine accident reporting systems, different backgrounds of investigators and researchers, and different research objectives have different impacts on the analysis results of management failures. Furthermore, in the analysis of collisions, Chauvin et al. (2013) summarised the management factors as resource management and

Table 4
Relevant papers related to the analysis of accident influential factors.

Influential factors	Human factors			Ship factors			Environmental factors		Management factors		Accidents factors		
References	Human error	Communication	Experience or knowledge	Fatigue	Ship particulars	Voyage statement	External environment	Navigational environment	Administration	Company	Ship	Accident type	Time
Chen et al. (2020)	✓				✓		✓	✓				✓	✓
Akyuz (2017)	✓		✓	✓			✓	✓		✓			
Chae et al. (2021)	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓		
Weng and Li (2019)	✓		✓	✓	✓	✓	✓	✓				✓	✓
Qiao et al. (2020a)	✓	✓	✓	✓			✓		✓	✓	✓		
Celik and Cebi (2009)	✓	✓	✓	✓			✓		✓	✓			
Chen et al. (2019)	✓				✓							✓	✓
Grabowski et al. (2009)	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓
Chauvin et al. (2013)	✓	✓	✓	✓			✓	✓	✓	✓			
Akyuz (2015)	✓	✓					✓	✓	✓	✓			

operational processes, in which through a case study it was found that 47% of the ships involved in the collision had problems with ship safety management system and inspection procedures, mirroring the importance of management factors of marine accidents. In fact, the analysis of management factors can not only improve the safe operation of ships and the situational awareness of crew members, but also improve the management and organisational mechanisms of the relevant shipping companies and maritime authorities.

At the same time, accident factors (mainly the types of accidents) have a strong influence on marine accidents as well. The focus of the analysis of influential factors varies against different types of accidents. Chen et al. (2020) analysed the relationship between different accident types and the severity of marine accidents, and found that sinking and collision had a greater impact on the severity of damage, while hull structural failures and grounding had a relatively less impact on the severity of an accident.

In general, ship factors can be further subdivided into ship type and ship scale (Mansyur et al., 2021; Wang et al., 2021b). Weng and Li (2019) analysed marine accidents in the waters of Fujian Province, China. This study found that small vessels (e.g., fishing vessels) were more likely to be involved in marine accidents, while vessels transporting cargo of a particular nature were more likely to be involved in serious marine accidents. Chen et al. (2019) analysed the weight of each ship type in total loss accidents. The comparison shows that the LPG, Ro/Ro and chemical tankers are more likely to have a total loss accident. The main reason for this is that as trade demand increases, cargoes tend to diversify, which increases the risk of accidents for ships carrying specific cargoes.

It is evident that ship factors are relatively easier to quantify and analyse than human and management factors. However, for the developing MASS, mechanical failures and cyber security pose a great threat to the safe operation of MASS. If a ship's key control systems fail mechanically or if cyber-attacks and interference occur, wrong decisions and loss of signals can lead to different types of accidents. Therefore, the assessment of possible accident risks in MASS becomes one of the directions for future development. Firstly, the autonomous navigation systems used in MASS need to control the ship-related mechanical equipment to perform their work. However, the mechanical failures of which the repair and maintenance are human dependent become much more concerned in MASS compared to conventional ships (Chae et al., 2020). Abaei et al. (2021) used the knowledge of professional engineers to assess the reliability of a particular main engine. This study found that it took 912 h of continuous operation for the main engine before reaching a predetermined threshold for a serious failure, this was much larger than the predetermined target of 500 h. At the same time, researchers have also proposed a risk management approach of cyber security for MASS. For example, Amro and Gkioulos (2022) proposed a risk management method called Threat-Informed Defence-in-Depth (TIDD), which can complete the assessment, simulation, inspection and adversarial simulation of cyber security postures. The shipping industry should gradually raise the awareness of cyber security, and adopt a combination of technology and management to enhance the cyber security defence capability of ships. This will also be an important prerequisite for the smooth operation of MASS (Tam and Jones, 2018).

Environmental factors mainly take into account the ship's navigational position as well as external environmental conditions (e.g., visibility and weather conditions). Weng and Li (2019) conducted an analysis of environmental factors during navigation, and found that the probability of a general accident was higher in coastal/harbour/port areas than those in other waters. This is mainly due to the greater density of vessel traffic in these areas, which also makes vessel operation more difficult. Chen et al. (2019) analysed specific waters on a global scale and found that the West Mediterranean and West African were locations where merchant vessels were more active and more prone to ship total loss accidents. As one of the extremely special navigation environment, more and more attention has been paid to the navigation environment in Arctic waters (Xu et al., 2022). With the receding summer sea ice, the potential for new routes in Arctic waters has increased. Therefore, the assessment of the risks of environment factors in the Arctic can be helpful to develop Arctic routes and ensure the navigational safety of ships. Studies have mentioned that the navigational environment in Arctic waters is relatively more complex (Fu et al., 2018; Khan et al., 2018). Due to the uncertainty of channel conditions and harsh climatic conditions in Arctic areas, the likelihood of ship-ice collision and ship sinking in ice accidents is higher in the Arctic than in other waters (Fu et al., 2021; Shu et al., 2023).

4.1.2. Consequences of marine accidents analysis

The consequences of marine accidents can be analysed in terms of casualties, ship damage and the environment, as well as the factors that influence the consequences of accidents, as shown in Table 5.

For the analysis of casualties and ship damage of marine accidents, human factors are also a key component in influencing the consequence of accidents. Vinagre-Ríos and Iglesias-Baniela (2013) proposed a similar view of point in their study and suggested that the psychophysical capabilities of the crew were an important factor in an accident, and that a lack of knowledge and experience at sea could lead to a lack of psychophysical capabilities.

Due to higher average number of casualties in sinking accidents, Weng et al. (2018) investigated the factors associated with the casualty in marine accidents, and found that of all accident types, sinking was highly correlated with fatalities in marine accidents. The result was also confirmed in a previous highly cited paper (Weng et al., 2016). In this study, Weng et al. (2016) noted that adverse weather conditions can increase the likelihood of casualties in marine accidents. For every 100 marine accidents in adverse conditions, there was the potential for approximately 28 fatalities or missing persons. Moreover, when accidents occurred at night, the number of casualties was greater than the number of those that occurred during the day (approximately 26% higher casualties). There was a similar study to cross-check the results. Li et al. (2021a) analysed the effect of different influential factors on the damage to the vessel, injury to the personnel and contamination of the environment, respectively. In the analysis, the influential factors "Time of day" and "Wind and waves" were positively correlated with vessel damage. Therefore, to avoid the occurrence of a serious marine accident, ships should pay close attention to weather conditions.

A number of studies have also revealed that ship-to-ship collisions can also cause some casualties and damage to ships. Through these studies it can be generally found that fishing vessels are more likely to suffer damage to their hulls in accidents. This further illustrates the ship scale would lead to different consequences of accidents. For example, vessels larger than 500 gross tons have a greater impact on the extent of damage to the vessel than ones larger than 10,000 gross tons. All these findings have also been confirmed by Mansyur et al. (2021), in which the overall influence of relevant factors on accident consequence were analysed based on an ordered logistic regression model. Sinking accidents, distance from coastal areas, harbours, high winds and strong currents, fishing boats, yachts and sailing boats were identified as the factors most likely to lead to more serious accidents. Obisesan and Sriramula (2018) stated that the probability of ship damage following a ship collision in an ice area was 0.5536, with the angle of collision being the largest factor affecting the extent of ship damage. Fu et al. (2018) used a fuzzy fault tree model to quantify the risk of ship stuck in Arctic waters, and found that a ship had a high probability resulting in ship drift, listing or even hull damage and sinking if it trapped during navigation from ice areas, and results also varied with different environmental conditions.

Moreover, the analysis of environmental issues is also an important part of the analysis of the accident consequences. The environmental impact of marine accidents is mainly due to oil spills or hazardous material spills caused by ship accidents (Eski and Tavacioglu, 2022; Lu et al., 2019; Soares et al., 2020; Vanem et al., 2008; Yip et al., 2011). It is worth noting that this study is concerned with the issue of environmental pollution in marine accidents, as shown in Table 6. Therefore, this study does not consider the issue of environmental pollution due to emissions from ships during navigation. Some studies focused on the location of the pollution caused by marine accidents. This is because when a marine accident occurs closer to land, the pollution caused by the accident is more likely to have an impact on the human living environment (Eski and Tavacioglu, 2022; Sewwandi et al., 2022; Soares et al., 2020). In addition, the issue of environmental pollution in Arctic waters has gained widespread attention because marine accidents that occur in the Arctic waters can have more serious impacts on the local natural ecosystems (Lu et al., 2019; Nevalainen et al., 2019).

Oil spills at sea can pose a serious threat to the marine ecosystem and human life. Due to the specific nature of their cargo, oil tankers are more likely to cause serious oil spills. Vanem et al. (2008) have analysed the damage caused by oil spills from tankers. It was found that the average clean-up cost per tonne of oil spilled was US $16,000 and the environmental and socio-economic damage was up to US $24,000. Yip et al. (2011) analysed the structure of tankers involved in oil spills in marine accidents, and found that prior to 1995, most of the world's tankers were of single-hull construction. This resulted in a high likelihood of cargo leakage from tanker hulls in the event of an accident. With the advent of double-hulled tankers, this change in structure had reduced the likelihood of oil spills on tankers and barges by 62% and 20%, respectively.

Similarly, the main cause of chemical pollution at sea is also due to cargo spills during accidents. However, unlike oil spills, chemical spills are usually not easily recovered. As a result, chemicals are more readily

Table 5
Relevant papers related to the analysis of casualties and ship damage.

Reference	Casualties	Ship damage
Weng et al. (2018)	✓	
Weng et al. (2016)	✓	
Li et al. (2021a)	✓	✓
Mansyur et al. (2021)	✓	✓
Vinagre-Ríos and Iglesias-Baniela (2013)	✓	✓
Xing et al. (2020)	✓	
Xue et al. (2021)		✓
Wang and Yang (2018)	✓	✓
Akyuz and Celik (2018)	✓	
Browne et al. (2022)	✓	

Table 6
Relevant papers related to the analysis of pollution.

Reference	Pollution			Location		
	Oil spill	Chemical spill	Plastics pollution	Coastal area	Iced water	Port
Sewwandi et al. (2022)			✓	✓		
Lu et al. (2019)	✓				✓	
Vanem et al. (2008)	✓					
Yip et al. (2011)	✓					
Nevalainen et al. (2019)	✓				✓	
Soares et al. (2020)		✓		✓		
Eski and Tavacioglu (2022)		✓				✓
Zhu et al. (2022a)	✓			✓		
Zalesny et al. (2017)				✓		
Zhu et al. (2022b)						✓

soluble in seawater and spread more rapidly (Häkkinen and Posti, 2014). Soares et al. (2020) used a chemical numerical dispersion model to analyse the dispersion of toxic and hazardous substances in chemicals in water and found that chemicals from a marine accident spread 10.5 km to the north and 29 km to the south over a period of three days. This result also confirms the corresponding view. In addition, the loading, unloading and berthing of goods are also possible to lead to leakage. Eski and Tavacioglu (2022) summarised the reports on dangerous goods spills in ports published by IMO between 2000 and 2020 and analysed chemical spills in waters around ports. The study found that the risk of chemical spills during loading, unloading and berthing would significantly increase. Therefore, during cargo handling and berthing, especially for chemical vessels and tankers, more attention should be paid to operational safety and regulations.

Furthermore, some studies have focused on accident pollution in coastal areas and near ports. For accident pollution caused by coastal areas, Zalesny et al. (2017) developed an algorithm using an ocean dynamics model, and assessed the displacement of accident pollution in coastal areas of Finland. Zhu et al. (2022a) used AIS data to identify the hazard/hazards of accidental oil spill pollution in waters off the coast of China. The study classified five risk zones based on oil volume, oil spill volume and accident probability. Among them, the BOHAI Sea, the ZHUJIANG water and the waters off Hainan Province were high risk areas with a relatively high environmental risk of oil spills. Similarly, for port waters, Zhu et al. (2022b) used Bayesian networks to assess the emergency response capability of the ZHOUSHAN Port in China for accident pollution. This study found that the harbour environment as well as emergency preparedness had a greater impact on the emergency response to accident pollution from ships in the port area. Lu et al. (2019) noted that the type of oil, the size of the spill, the location of the incident and the proximity to the port had a greater impact on the severity of the spill. For example, heavy and medium oils had a higher probability of recovery than gasoline and light oils; being closer to the port also allowed for faster pollution control. This result is also validated by the analysis of Nevalainen et al. (2019). All these studies proved that pollution from marine accidents in coastal areas and ports will have serious consequences. This is also because coastal areas and ports are closer to the living environment and such accidents are more likely to endanger human life.

In fact, environmental pollution from ships in the ice zone has gained more attention due to the increased complexity of the navigational environment and the increased navigable waters in the Arctic (Xu et al., 2022; Zhang et al., 2019). In particular, after a ship spills oil in the Arctic, the oil will go through both weathering and transport processes. This can lead to emulsification, encapsulation and dispersion of the oil, which can have a more serious impact on the surrounding ecology (Afenyo et al., 2016). Nevalainen et al. (2019) conducted a risk assessment of oil spills in the Arctic, and pointed to a greater impact of the type of oil on the potential hazards of the accident. Therefore, the analysis of pollution from marine accidents in the Arctic should receive more attention. This is an important trend for future developments in the field of marine accident consequence analysis.

4.2. Methodology of marine accidents analysis

It can be seen from the clustering results in Table 3, Figs. 7 and 8 that a number of researchers have used a variety of methodologies to study marine accidents.

4.2.1. Traditional methodology of marine accidents analysis

In order to drive the most representative methods in marine accident research, HFACS, AHP, TOPSIS and fuzzy theory are selected as the main methods to be described respectively. This is based on the statistical analysis from the clustering results in Table 3, Figs. 7 and 8, as well as combined with manual inspection.

As for the research methodology of marine accidents, the HFACS has been considered as a general approach to analyse human factors (Chauvin et al., 2013; Uğurlu et al., 2020; Zhang et al., 2019). The initial HFACS structure is specifically explained into four system levels (Wiegmann and Shappell, 2016), with the development of research on human factors, the analytical framework of HFACS has been refined by many researchers in the maritime field and applied to the analysis of marine accidents, as shown in Table 7. Yildiz et al. (2021) found that there was an interaction between operation conditions and unsafe behaviour in collisions by taking weather and sea conditions into account. Both Chauvin et al. (2013) and Chen et al. (2013) modified the structure of HFACS. The former divided external conditions into regulatory factors and others in the first stage, while the latter redefined the initial HFACS structure in the unsafe behaviour stage in terms of failures of rules, knowledge and skills. This allowed the revised model to be more comprehensive and suitable in its analysis. In addition to the structural modification, HFACS can also be combined with other methods. Sarıalioğlu et al. (2020) used HFACS to classify and summarise the factors affecting cabin fires, concluded that the age of the ship, mechanical fatigue and maintenance errors were the main factors influencing cabin fire accidents. Soner et al. (2015) obtained the root factors that contribute to fire accidents on board a ship by a combination with HFACS and FCM technique. It was found that those factors were reflected in a number of dimensions such as unsafe behaviour, regulation and organisational influences. Therefore, this study further considered the ship's system mechanisms, operation and execution mechanisms as the main causes of fires from a macro perspective.

Comprehensive evaluation methods also have frequent applications into marine accident research, including AHP analysis and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). AHP analysis is an effective decision-making method structured on three levels: objective, criterion and solution (Arslan and Turan, 2009; Tonoğlu et al., 2022). In the analysis of marine accidents, AHP analysis can be used to determine the influential factors of accidents and the importance of each factor. For example, Lee and Kim (2013) analysed the significance of 20 influential factors under five risk categories: natural, channel, traffic, ship and salvage conditions, identified traffic conditions and visibility as the highest weighted categories and factors respectively. Oraith et al. (2021) explored the human factors affecting pilotage accidents and classified them into five main categories. Subsequently, the AHP analysis method was used to find that non-technical

Table 7
Applications of HFACS to the research of marine accidents.

Reference	Name	Structure
Yildiz et al. (2021)	HFACS-PV	1. Operational Conditions 2. Unsafe Acts 3. Pre-conditions for Unsafe Acts 4. Unsafe Supervision 5. Organizational Influences
Sarıalioğlu et al. (2020)	HFACS-PV&FFTA	1. Organizational influences 2. Unsafe supervision 3. Preconditions for unsafe acts 4. Operational conditions
Soner et al. (2015)	HFACS-FCM	1. Unsafe acts 2. Pre-conditions for unsafe acts 3. Unsafe supervision 4. Organization influences
Chauvin et al. (2013)	HFACS-Coll	1. Outside factors 2. Organizational Influences 3. Unsafe leadership 4. Pre-conditions for Unsafe Acts 5. Unsafe acts
Chen et al. (2013)	HFACS-MA	1. External factors 2. Organizational influences 3. Unsafe supervision 4. Preconditions 5. Unsafe acts

skills shortcoming and technical skills shortcoming were the two causes with the highest weights of 33.84% and 30.48%, respectively.

TOPSIS is a comprehensive evaluation method that ranks the distances between the evaluated objects and the optimal solution to complete a multi-objective decision analysis (Behzadian et al., 2012; Zhang et al., 2022b). TOPSIS is similar to AHP analysis in which both methods are capable of solving the Multi-Criteria Decision Making (MCDM) problem, and TOPSIS is to normalise the original data and the matrix (Wu et al., 2018). The relative proximity of each evaluation object to the optimal solution is the distance between each evaluation object and the optimal as well as the sub-optimal solution (Behzadian et al., 2012). In the field of marine accident research, TOPSIS has been used to some extent in accident prevention, decision making and safety assessment. Fan et al. (2020d) used TOPSIS to explain the priorities between different strategies using accident types as multiple criteria. The study identified three human factors that need to be considered first in the development of a marine accident prevention process, which included safety culture, information and clear instructions. In addition, Othman et al. (2015) determined the factors which affect the crew members' mental state. The study concluded that the highest priority among the factors influencing the psychological state of crew members was the working environment, e.g., the psychological stress of crew members on board LNG and LPG ships was larger than that of container ship, as the handling standards on board LNG and LPG ships were higher and the consequences of accidents were usually more severe. This also provided new ideas for accident prevention strategies on different ships and in different environments.

As the application of uncertainty reasoning methods, such as fuzzy reasoning methods, traditional marine accident research methods are combined with fuzzy theory, as shown in Table 8. This further enriches the methods of marine accident investigation and research, and to some extent settling the limitations that exist in traditional methods. Tonoğlu et al. (2022) used expert knowledge and historical accident data to analyse the navigational risk of ships in different locations in the Turkish Strait. The study eliminated the problems that arise in estimation, such as subjectivity of expert knowledge and incompleteness of historical data, by using fuzzy numbers. Similarly, Hsu (2012) assessed the role of port departments in the evolution of marine accidents and concluded that the professionalism of personnel was a major factor in ensuring safe ship navigation. The combination of fuzzy theory and TOPSIS also helped to improve the flexibility of decision making. Wu et al. (2016) used fuzzy logic to fuzzify historical data to obtain the attribute values of relevant accident influential factors after completing fuzzy inference and defuzzification. This study then introduced TOPSIS for decision analysis, providing multiple options for the safety control of runaway vessels. Liu et al. (2016) also combined fuzzy logic with TOPSIS to measure the uncertainty of alternatives using a variance matrix, i.e. even when the same options are available, various operators will choose different approaches. This approach also provided new ideas for safety assessment of inland waterway traffic accidents. In addition, Navas de Maya and Kurt (2020) used fuzzy cognitive maps (FCMs) to investigate the interrelationships between accident influential factors and found that the key factors in collisions of bulk carriers were lack of communication. Qiao et al. (2020a) used sand carrier accidents as the main research object and analysed that the most critical human factors in sand carrier accidents were unsafe behaviour and unsafe management by using a dynamic fuzzy Bayesian network model. In summary, fuzzy theory has obvious advantages in the analysis of marine accidents, it can control and improve uncertainty scenarios, which makes fuzzy theory as one of the attractive research topics in the current stage (Wu et al., 2020).

Table 8
Applications of fuzzy reasoning methods.

Reference	Applications of the fuzzy theory	Advantages of using the fuzzy theory
Tonoğlu et al. (2022)	FAHP-PRAT	To eliminate subjective errors arising from expert knowledge and inconsistencies arising from insufficient data
Hsu (2012)	FAHP	To eliminate subjective errors arising from extreme values
Wu et al. (2016)	Fuzzy TOPSIS	The integration of influencing factors
Liu et al. (2016)	Fuzzy TOPSIS	To provide greater flexibility in the ranking of options with similar expected values
Navas de Maya and Kurt (2020)	Fuzzy Cognitive Maps	To eliminate or control the subjectivity in results
Qiao et al. (2020a)	Fuzzy Bayesian Network	To develop the characteristics of flexibility and uncertainty handling

4.2.2. Emerging methodology of marine accidents analysis

Machine learning (ML) is an emerging methodology compared to traditional research methodology. ML has also been widely used in recent years in research on marine accidents and has further refined existing research (Rawson and Brito, 2022; Uyanık et al., 2021; Zhang et al., 2023). ML is a computational tool that covers knowledge of statistics, probability theory, approximation theory and complex algorithms and can effectively improve learning efficiency (Filom et al., 2022; Zhang et al., 2021b). The main rule of ML is to enable computers to automatically acquire knowledge and skills through learning, and then to continuously improve their performance (Zhang et al., 2022a). ML can be classified according to its learning capabilities as Supervised Learning (SL), Unsupervised Learning (UL) and Reinforcement Learning (RL) (Filom et al., 2022). Different classifications encompass different ML algorithms (Atak and Arslanoğlu, 2022; Hou et al., 2022). Relevant ML algorithms are also widely used, such as tree algorithms, Bayesian networks (BN), logistic regression (LR), K-means, Markov chains (MC), support vector machines (SVM) and artificial neural networks (ANN), as shown in Table 9. Meanwhile, the integration of big data with relevant algorithms has led to better performance of relevant ML methods in the analysis of marine accidents (Rawson and Brito, 2022; Tang et al., 2022; Zhang et al., 2021b), as shown in Table 10.

Tree algorithms belong to a commonly used classification algorithm of SL. In marine accident research, some researchers use fault trees to reason and rank the main factors that lead to accidents. Ugurlu and Cicek (2022) used fault trees to qualitatively and quantitatively calculate the accident probability and rank the factors contributing to ship collisions. Through analysis, the study found that human factors contributed to a 94.7% probability of a collision occurring. Another study combined fuzzy set modelling with fault trees to analyse the impact of human factors in marine accidents. This combined approach was able to deal with the uncertainty of the data in question, which enhanced the data handling capabilities of the fault tree model and reduced errors due to missing data (Gul, 2020; Zaib et al., 2022).

SVMs are a ML method for classification and regression that have the advantage of being highly interpretable and not relying on statistical methods, thus simplifying traditional classification and regression problems (Atak and Arslanoğlu, 2022). Zheng et al. (2020) proposed a SVM-based approach for quantitative assessment of ship collision risk. The approach was used to quantitatively assess ship-to-shore encounters, cross-encounters and overtaking scenarios with its validity verified. Park and Jeong (2021) collected ship-related parameters and estimated

Table 9
Classification of machine learning algorithms.

ML	Tree algorithms	SVM	BN	LR	K-means	ANN	Q-Learning algorithms
SL	✓	✓	✓	✓		✓	
UL					✓		
RL							✓

Table 10
Applications of machine learning to marine accident analysis.

Reference	Methodology	Input	Output	Positive Attributes	Limitations
Zaib et al. (2022)	Fuzzy Fault Tree Analysis (FFTA)	A real-life case	The failure probability of the causes	The methodology is able to quantify the human factor and improve the problems caused by the lack of data.	The lack of expert opinion can have an impact on the results of data analysis.
Ugurlu and Cicek (2022)	FTA	513 collision accidents reports	Influential factors in collision accidents	Visualise the relationship and logic between the factors and top event. It has a better performance in closed loops.	The method lacks consideration of the interactions between factors.
Park and Jeong (2021)	SVM + RVM	AIS data	The risk of collision	Improved machine learning models have better performance and can determine collision risk more accurately.	The method does not take into account the influence of human factors.
Atak and Arslanoğlu (2022)	SVM + NB	16 accident cases	Accident causes	The method has better classification accuracy and better prediction results.	Over-fitting should be prevented.
Zheng et al. (2020)	SVM	The states of ships	Collision risk	The algorithm further takes into account the consequences of collisions and it can be implemented more easily with current equipment.	The method does not take into account the influence of human factors, environmental factors, etc. on the handling of the ship.
Zhao et al. (2021)	BN + Big Data	Two hundred accident reports	Relationship between risk influencing factors	The method is able to integrate the impact of multiple factors on accidents and the large data can also enhance the training ability of the model.	No further validation of the structure of the model has been undertaken in a relevant way such as expert knowledge validation.
Uğurlu et al. (2020)	BN + HFACS	A total of 109 accidents	Accident formation patterns	The method has good applicability and adaptability and can be extended to different waters for analysis.	More data could improve the reliability of the study.
Afenyo et al. (2017)	BN	Arctic past accident data	Causative factors in the potential scenarios	The method takes into account the interactions between the factors.	The method requires a high level of accuracy of the data source.
Fan et al. (2020b)	NB	109 accident reports	Influential factors in marine accidents	The method provides a better analysis of the impact of the factors on the accident.	Lack of data can affect the prediction results of the method.
Mansyur et al. (2021)	OLR	1207 accidents	The relationship between factors and the accident severity	The method provides good analytical results on the relationship between relevant objective variables.	The method requires a high degree of accuracy in the data source.
Kim et al. (2017)	LR	4-month ship trajectory	To assess near-miss collision risk	The method enables a probabilistic calculation of accidents due to relevant factors.	The method needs to be further investigated by other factors such as human factors in the actual situation.
Uyanık et al. (2021)	Multiple Regression + Random Forest	6183 h of information	Relationship between the environmental variables	The study uses a variety of methods to analyse visibility. Moreover, the gradient lifting method improves the estimation processes.	Some of the methods applied in this study require a high level of relevant expertise and are difficult to reproduce.
Zhang et al. (2021c)	K-means + Kernel Density Estimation (KDE)	5, 726 accident records	The overall profile of global marine accidents	The study validates the potential of geospatial technology for application in the field of maritime security.	The method requires a high quality and quantity of database.
Hou et al. (2022)	K-means	3672 pieces of data	A decision-making model for port state control inspection	The method has better accuracy than a random guess and provides wider coverage of ship factors.	The model still needs more qualified data for model refinement.
Xuan et al. (2017)	Markov Chain Monte Carlo (MCMC)	881 accidents	The analysis of traffic risk in waters adjacent to land	The method improves the efficiency of the simulation by simplifying the sampling procedure.	State-discrete and time-continuous Markov processes need to be discussed further.
Faghih-Roohi et al. (2014)	MCMC	546 accidents	To assess accident risk in marine transportation	The method is more inclusive in terms of database content and size.	The method needs additional and more effective methods to validate the model.
Qiao et al. (2020b)	ANN + FFTA + HFACS	38 accidents	The relationship between human factors and the marine accidents	The method is a fully data-driven approach with good objectivity.	The method did not consider of the correlation between the factors.
Liu et al. (2020)	Recurrent Neural Network (RNN)	AIS data	A real-time prediction framework	The method can improve the efficiency and reduce the complexity of collision risk quantification.	More training data and a more advanced concept of ship domain geometry are needed.

the collision risk of a ship using SVM and the relevance vector machine (RVM). The comparison showed that both methods were capable of assessing the collision risk of a ship. However, the traditional SVM model required a larger number of vectors and contained unnecessary calculations, thus taking longer to train.

Bayesian analysis methods are methods for calculating posterior probabilities and inferring unknown parameters based on Bayes' theorem (Wu et al., 2021). In the field of marine accident research, Bayesian networks and Naïve Bayes are two commonly used methods (Adumene et al., 2022; Aydin et al., 2021; Senol and Yasli, 2021). BN, also known as directed acyclic graphical model, and can be used to solve the problem of uncertainty and incompleteness of accident information (Cao et al., 2023; Xu et al., 2022). Afenyo et al. (2017) used BN to investigate Arctic shipping accident scenarios, and found that human error was the most influential factors in ice navigation. Uğurlu et al. (2020) combined BN with HFACS to examined and analysed the marine accidents, and found that unsafe crew behaviour was the most influential factor in collisions, while ship structure and age were key factors in ship grounding and sinking. Zhao et al. (2021) addressed this issue to some extent by using big data to train models on BNs. The study found that MASS face a higher risk of collision in crossing situations, though they equally reduce the impact of human and some environmental factors (visibility and night) on accidents. In addition, Naïve Bayes has its own unique advantages in the classification process. The robustness of the Naïve Bayesian Network (NBN) is better in terms of not showing much variability for different types of data sets, and performing well in cases where the relationships between variables are more independent (e.g., mutually independent accident types). Fan et al. (2020b) used the NBN to analyse the influence degree of different risk factors on different types of accidents. The study found that fishing vessels were more likely to have man overboard accidents, capsize during towing operations, collide when navigation in transit, and run aground when there was poor information on board.

Regression models are often utilised to quantitatively analyse the relationships between different variables. In the field of marine accident research, regression analysis is often used to study the relationship between accident influential factors and the relationship between different accident types or different accident severity and the influential factors (Mansyur et al., 2021; Weng et al., 2019). Kim et al. (2017) conducted an analysis of Near-Miss Ship Collisions accidents using a dichotomous logistic regression approach, where Near-Miss Ship Collisions were treated as the dependent variable. Through this study, distance to closest point of approach, time to closest point of approach and collision avoidance variance were put into the logistic regression model as the independent variables in the model analysis. It was found that all these variables had a negative effect on the occurrence of Near-Miss Ship Collisions, and Collision Avoidance Variance (CAV) had a greater effect on the occurrence of overtaking than the other variables. Mansyur et al. (2021) used an ordered logistic regression model to analyse the relationship between influential factors and accident severity. It was found that the ordered logistic regression model was able to perform regression analysis on dependent variables with multiple classifications. Therefore, the model was suitable for the analysis of accident severity where the dependent variable has multiple discrete classifications. In addition, multiple linear regression, gradient boost regression and ridge regression algorithms have also been used in the study of marine accidents. Uyanık et al. (2021) carried out a comparative analysis of the effect of visibility on the safe navigation in the Istanbul Strait using the above regression models. The study found that visibility was highly negatively correlated with humidity. In addition, gradient boost regression showed better predictive performance in this study, which was mainly related to the flexibility feature of this method.

In addition to the aforementioned main methods, K-means, MCMC and Neural Network are also ML algorithms used in marine accident analysis. K-means algorithm focuses on iterative solving. The approach works by calculating the distance between each object and its sub-clusters and assigning each object to the cluster centre nearest to it and repeating until some termination condition is met. Hou et al. (2022) developed an unsupervised algorithm based on K-means. The algorithm was able to classify ships with different risk types and thus improved port state control inspection decisions. Zhang et al. (2021c) developed a geospatial technique based on K-means to classify areas of marine accidents worldwide into different clusters and summarise the characteristics of accidents occurring within the different clusters. The study pointed out that the highest number of accidents occurred around the UK, Denmark, Singapore and China, while the proportion of collisions in East Asia reached 40%, a result that may also be related to the high density of routes and the complex maritime geography of these waters. The MCMC method is often used to assess maritime navigation risk. This is because ship navigational risk is essentially a complex stochastic phenomenon, and the MCMC method can realize the numerical calculation of multivariate random variables distributed in non-standard form. Xuan et al. (2017) and Faghih-Roohi et al. (2014) both used MCMC to probabilistically calculate the risk of navigation in different waters. There were also differences in the risk of accidents of different severity in a given navigational water. For example, the mean probability of incidents, accidents and serious accidents in waters off Australia was 0.1004, 0.0059 and 0.0069, respectively (Faghih-Roohi et al., 2014). In addition, ANNs and RNNs are also used in the field of marine accident research, where ANNs utilise parallel, distributed processing structures to learn and process relevant information. Qiao et al. (2020b) combined the ANN model developed by HFACS and FFTA to evaluate the human factors affecting accidents. The ANN model was found to be effective in handling uncertainty, dynamics and non-linearity in the human factors through model validation. This can build a dataset to complete the model training and then complete the risk prediction of collision incidents.

5. Discussions

5.1. The main findings of this study

From the analysis of collaboration networks, *Safety Science, Ocean Engineering, Reliability Engineering & System Safety* and *Accident Analysis and Prevention* are the four most cited journals in the research field of marine accident. In terms of co-authorship network, there is close cooperation between the authors, countries, regions and research institutions. Among them, Wuhan University of Technology, Shanghai Maritime University, Liverpool John Moores University, Istanbul Technical University, Dalian Maritime University are the top five institutions in terms of the number of publications. China, Turkey, South Korea and the United Kingdom are the four countries with the highest number of publications in the field of marine accident research.

By using CiteSpace and manual screening, the marine accidents research hotpots are classified into two areas: research subject and methodology. The main research subjects include the influential factors and consequences of marine accidents. On the one hand, human error is one of the key factors causing marine accidents. The studies on human factors mainly focus on human error, communication problems, experience and skill levels, and physical and mental conditions. The process of quantifying the human factor is also one of the underlining issues that need to be addressed. On the other hand, the consequences of marine accidents are also the important research topics, which include casualties, ship damage and environmental influence. It is noteworthy that most of the studies analysing environmental pollution have focused on the relationship between the location of the accident and the pollution situation. In addition, the analysis of the factors influencing the severity of accidents also provides new ideas for the prevention of serious accidents.

This study then analyses the research methodology related to the research field of marine accident in terms of both traditional and emerging methodologies. Through the study, it is found that the traditional methods like HFACS, AHP analysis and TOPSIS methodologies still exist in some application scenarios. At the same time, many traditional marine accident research methods are combined with fuzzy theory, and this further enriches the means of marine accident research. In addition, machine learning, a current hot topic in the research of marine accident, has been applied in marine accident research. Machine learning includes some algorithms such as FTA, SVM, BN, LR, K-means, MC and ANN. With the continuous development of machine learning techniques and their integration with big data, the analysis of marine accidents has become more accurate and comprehensive.

5.2. The innovations of this study

Based on the above findings, this section provides further comparisons between relevant reviews, as shown in Table 11.

Compared with relevant reviews, firstly, the database of this study is larger and the literature covered is more comprehensive. Given that 491 articles in the field of marine accident research during the period 2000–2022 are selected to conduct literature analysis, this is actually a broader coverage than relevant marine reviews such as Sepehri et al. (2022), Goerlandt and Montewka (2015), Adumene et al. (2022), and Gil et al. (2020).

Secondly, this study focuses more on the last two decades, especially including the analysis of marine accident studies from 2015 to 2022. Although Luo and Shin (2019) selected 572 articles for literature analysis, their study only analysed literatures from 1965 to 2014 and failed to analyse the research content and research trend in the recent 8 years. Therefore, the literature database of this study is up to date.

Thirdly, in terms of the research methodology, Bibliometrics, knowledge mapping and Scientometrics are used to provide a new sight

Table 11
Comparison of this study with relevant marine accident review studies.

Reviews	Research sources	Research methodology	Characteristics	Contents
Kaptan et al. (2021)	5 HFACS structures	Literature research; Summarisation;	The use of HFACS-COLL; The use of HFACS-MA; The use of HFACS-ground; The use of HFACS-SIBCI; The use of HFACS-PV;	This study compared and analysed various modified HFACS structures, showing that the level of external factors and operational conditions were the main differences between the developed structures. And the study provided a detailed account of the choice between models.
Luo and Shin (2019)	572 papers	Literature research; Summarisation;	Evolution of spatial location; Evolution of majors accident; Evolution of topics; Evolution of causes of accident; Evolution of contents; Trend of methodology; Evolution of data sources;	This study identified the evolution and changes of researchers, journals, the major issues, the research methods and the data sources.
Sepehri et al. (2022)	110 papers	Systematic literature review;	The analysis of the applications and technologies of shipping 4.0; The introduction of the conceptual framework;	This study conducted a comprehensive review on the impact of related technologies and applications in Shipping 4.0 on maritime accidents, analysed the application fields of related technologies and integrated a shipping 4.0 risk management framework.
Goerlandt and Montewka (2015)	58 papers	Classification; Summarisation;	The introduction of risk analysis science approaches; The applications of risk analysis science approaches in marine; The discussion of risk analysis science application area;	This study provided a comprehensive review of risk definitions and analysis methods in the maritime domain, compared different scientific methods of risk analysis and put forward suggestions for strengthening the scientific basis of risk analysis.
Adumene et al. (2022)	72 papers	Literature research; Summarisation;	The analysis of HOFs in marine; The challenges of HOFs; The future methodologies of HOFs analysis;	This study summarised the techniques and methods currently used in the analysis of HOFs in marine accidents, and proposed that data collection, human factor quantification, and analysis of HOFs on autonomous ships are the main challenges in this field.
Gil et al. (2020)	107 papers	Bibliometrics and research mapping; Systematic literature review;	The analysis of social and intellectual structure of DSS analysis; The comparison of relevant papers; The technology situation of DSS; The theme of DSS; The further works of DSS;	This study provided a systematic description of DSS in the field of marine accident prevention. And through the method of bibliometrics and visualisation technology, the social structure and intellectual structure among the articles were analysed.
This study	491 papers	Bibliometrics and research mapping; Scientometrics; Systematic literature review;	The analysis of current research network; The analysis of the research subjects; The analysis of the research methodology; The analysis of future research directions;	This study summarises the current journal, author, and country/institution status of research on marine accidents. Through cluster analysis of research hotpots, this study provides a systematic summary of marine accident research in terms of both research subjects and research methodology. In addition, this study discusses the future development of the marine accident research field based on current developments.

and in-depth review of marine accident research in this study. Most of the existed review papers are generally discussed in relation to the selected literature through manual analysis and manual classification of research themes and trends (Adumene et al., 2022; Kaptan et al., 2021; Luo and Shin, 2019).

Finally, this study focuses on analysing the current situation and trend of marine accident research from a more comprehensive perspective, rather than a certain method or subtopic. For example, Kaptan et al. (2021) reviewed the HFACS methodologies commonly used in marine accident research, analysed the characteristics and differences of each of the five HFACS models. Adumene et al. (2022) and Gil et al. (2020) analysed human factors and organizational factors (HOFs) and Decision Support Systems (DSS) in the specific marine accident, respectively, making these two review articles relatively limited in a certain research field.

5.3. The research directions of marine accident analysis

Furthermore, it is believed that a discussion of future research directions would be useful in helping researchers to clarify the focus of future work. Therefore, based on the above analysis, the research directions in the field of marine accidents are determined.

(1) The research of influential factors in the safety of MASS

In the context of the rapid development of autonomous ships, more and more attention has been paid to the analysis of safety-relevant influential factors of MASS (Liu et al., 2023). As the different stages of MASS, e.g., from conventional ships to remote control ships and finally to unmanned ships, the safety-relevant influential factors will accordingly change. The factors of remote control ships that need more consideration are the human-related factors, the cyber security and the reliability of the equipment (Zhang et al., 2020).

Firstly, it is worth noting that, for remote control ships, the point of interest in human factor will change from the ship's crew to the shore-based operator. This is because human work in ship operation will gradually be replaced with increasing intelligence and decision-making capabilities. However, shore-based remote control is a necessary stage for the safe navigation of remote control ships until the ship achieves the stage of fully unmanned autonomous navigation. The involvement of shore-based operators introduces new human factors, such as situational awareness error, overburden, etc. Therefore, human factors analysis for shore-based operators needs to be taken into account.

Secondly, ship equipment in general requires regular maintenance and repair. With fewer people on board, this poses new challenges for the stability of equipment on oceangoing ships with long operating cycles. On the one hand, the ship's equipment needs to be able to maintain a stable performance over a long period of time to support the safe navigation of the ship. On the other hand, there is also a need to have the response and recovery capability to be able to develop and implement appropriate reactions to restore damaged functions or services to the ship's equipment.

Thirdly, cyber security is an important component of autonomous ship navigation that cannot be ignored. With the development of ship intelligence, the communication and navigation information system, control system and ship equipment are increasingly interoperable through the network, and the interaction between ships and the outside world is increasingly frequent. While the security level of ship information network and control network is relatively low, the common software are all vulnerable to be attacked. In recent years, with the in-depth research of the network security system and the advancement of cryptographic technology, the cyber security problem is expected to be solved. As MASS evolves to the unmanned ship stage, the factors affecting marine accidents need to focus on four factors: ship factors, environmental factors, management factors and technical factors. This is because a fully unmanned ship will be able to navigate and operate independently of humans, avoiding the occurrence of marine accidents due to human error. This is also the ultimate goal of MASS.

(2) The research of accident prevention of Arctic navigation

Due to the global climate change, with rising temperatures and melting ice in Arctic waters, the commercial value of Arctic shipping routes has received widespread attention from countries around the world. However, as the threat of extreme weather and icebergs exists in the Arctic, the prevention of accidents to ships in the Arctic needs careful consideration. At present, the following safety risks need to be addressed: first, the risk of lack of facilities along the Arctic; second, the risk of unstable of communication and navigation equipment; third, the risk of poor visibility and navigation in icy areas at night; fourth, the risk of deviations in sea ice forecasts; fifth, the risk of frequent adjustment of Arctic routes and ice trapping (Christensen et al., 2022). Therefore, in response to the severity of the Arctic environment and the difficulty of risk assessment, there is a need to establish the Arctic shipping route risk assessment index system and the risk assessment model to carry out a comprehensive quantitative risk assessment for each Arctic shipping voyage.

In view of the high latitude and low temperature environment of the Arctic, studies on polar communication, navigation, life-saving equipment, low temperature operation and control technology are also needed. Furthermore, for the problem of more potential risks in Arctic shipping, studies related to Arctic navigational aids are necessary, including weather forecasting of Arctic environment, ice load monitoring of ship structure, intelligent situational awareness, video monitoring and risk visualisation warning, ship-shore guarantee of two-way communication and other technical issues. Through the continuous improvement of the safety and protection of navigation in the Arctic Ocean, the occurrence of marine accidents in the Arctic can be effectively decreased.

(3) The research methodology of marine accident analysis

The approach to the study of marine accidents has experienced continuous development in recent years. Due to the development of computer technology and the application of various algorithms in the marine industry, the emerging methodology in marine accident research could improve the reliability of the results and have great potential for future research. Moreover, using emerging methods, such as machine learning, deep learning and big data mining, allows to develop more advanced approaches or models to enrich the analysis method of marine accident, and then provide practical innovation to the prevention of accidents (Zhang et al., 2022a, 2023). On the one hand, emerging technologies can have more accurate predictions. Machine learning algorithms can analyse complex data sets and identify patterns that may not be immediately detectable by humans (Hellton et al., 2022). This can improve the accuracy of risk assessments and help to predict the likelihood of future accidents. On the other side, the combination of machine learning and big data mining can improve the decision-making ability. By providing more accurate and comprehensive data, emerging methods can help decision makers to make more informed decisions. This can help improve the overall safety and sustainability of the maritime industry.

However, there are still a number of issues that need to be addressed in the future development of the emerging approach. On the one hand, data quality and usability need to be further improved. In marine accident analysis, the data collected may be incomplete, inaccurate or inconsistent, which can affect the accuracy of predictive models and risk assessments. Furthermore, there is a lack of standardisation between data. Currently, the maritime industry lacks standardisation in data collection and reporting. This makes it difficult to compare data across ships, companies and regions, and can also affect the accuracy of predictive models. On the other hand, some of the current methods still require human expertise. However, the flourishing of emerging approaches are trying to fill this gap. This is because higher quality analysis results and more intelligent methods are important for the improvement of the safety of ships and preventing accidents. Based on the continuous advancement of methods, marine accidents will also be studied more thoroughly.

5.4. The implication of this study

As a review study of marine accident research, based on the analysis of the current literatures, this study not only summarises the research status and points out the future research direction, but also has the following practical contributions.

This study identifies current cooperation between journals, authors, institutions, nations and regions in the marine accidents research, and provides insights for global researchers working in the field. The study also demonstrates the current dominant journals and bodies of research, further encouraging global collaboration and innovation, particularly with regard to the enhancement of research methods and data processing. By understanding the geographical and spatial distribution of marine accident research globally, it will also encourage complementary cooperation between shipping enterprises and research institutions to promote the sustainability development of the shipping industry.

By reviewing the literatures in the marine accident research over a 20-year period, tracking the research frontiers, identifying current results and sorting out the evolution of research, this study provides a comprehensive and systematic introduction for researchers. This will help the academic community to understand the main achievements and shortcomings of current research, so that they can avoid repeating the work of others and find an appropriate starting point for their research.

Based on the research directions proposed in this study, it can help researchers to quickly understand future concerns of the marine accidents, as result in leading to breakthroughs and development of cutting-edge technologies. For institutions and regions involved in marine accident research, the research direction trends can help guide the applications and realisation of inter-institutional and inter-regional strengths in high-level technologies. For the shipping industry, this study can help practitioners to develop an awareness of sustainability developments, particularly in MASS, Arctic navigation and the development of emerging methodologies, which can contribute to the safety and efficiency of the shipping industry.

6. Conclusions

To provide a comprehensive review and summary of the marine accident research field, firstly, 491 literatures related to marine accidents are selected and summarised in this study. Secondly, CiteSpace and VOSviewer are used as scientometric analysis and information visualisation tools, and the collaboration network of journals, authors, nations/regions and institutions in marine accident-related research over the period 2000–2022 are analysed. Thirdly, the research hotpots and knowledge frontiers in the field of marine accident research are presented, which demonstrates a comprehensive insight of marine accident analysis. Fourthly, comparisons are made between this study and related review studies to highlight the contributions made by this study. Finally, this study suggests three future directions and implications for the field of marine accident research, which provides ideas for the development of marine accident research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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