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Review

A Systematic Literature Review of Maritime Transportation Safety Management

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Abstract: Maritime transportation plays a critical role in global trade, and studies on maritime transportation safety management are of great significance to the sustainable development of the maritime industry. Consequently, there has been an increasing trend recently in studies on maritime transportation safety management, especially in terms of safety risk analysis and emergency management. Therefore, the general idea of this article is to provide a detailed literature review of maritime transportation safety management based on 186 articles in the Web of Science (WOS) database published from 2011 to 2022. The purposes of this article are as follows: (1) to provide a statistics-based description and conduct a network-based bibliometric analysis on the basis of the collected articles; (2) to summarize the methodologies/technologies employed in maritime transportation safety management spatiotemporally; and (3) to propose four potential research perspectives in terms of maritime transportation safety management. Based on the findings and insights obtained from the bibliometric and systematic review, the development of a resilient maritime transportation system could be facilitated by means of data- or intelligence-driven technologies, such as scenario representation, digital twinning, and data simulation. In addition, the issues facing intelligent maritime shipping greatly challenge the current maritime safety management system due to the co-existence of intelligent and non-intelligent maritime operation.

Keywords: maritime transportation; emergency management; safety risk analysis; bibliometrics; research perspective

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1. Introduction

Maritime transportation is critical for global trade, and over 80% of global goods are delivered by ocean shipping [1]. According to the "*Review of Maritime Transport 2022*" issued by the United Nations Conference on Trade and Development, the global commercial fleet has increased sharply in the last three decades, which reflects an increase in global maritime transportation activities. The safety-related issues associated with maritime transportation are highly concerned with minimizing maritime accidents and their impacts on human life and the ocean environment. For this purpose, various risks involved in maritime transportation must be controlled to an acceptable/tolerable level [2]. In addition, in the case of heavy casualties or large-scale oil spill pollution, effective emergency management is critical to reduce the damage caused by these events. Meanwhile, search and rescue (SAR) requirements at sea also require effective emergency responses to reduce the loss of human life. To maintain maritime transportation safety at a satisfactory level, the International Maritime Organization (IMO) has taken proactive measures to promote safety in the maritime industry [3–5], such as the International Convention for the Safety of Life at Sea (SOLAS), the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), and the International Safety Management Code

(ISM). The International Convention on Maritime Search and Rescue has also come into use to enhance emergency collaboration globally. At the national level, various regulations and measures have also been adopted. For instance, the UK government supports the promotion of autonomous ships and invests actively in the research and development of new space technologies. The Danish government is improving the maritime information and communications technology (ICT) infrastructure under the regulatory framework of the European Union (EU) and the IMO. The Korean government has strengthened maritime safety through digital technology and seeks to create a big data platform in the maritime and fisheries sectors. However, catastrophic consequences in terms of human life losses, damage to commodities, and environmental pollution are still frequently reported. For instance, according to a report issued by the Ministry of Transport of the P. R. of China, there were a total of 237 human lives lost or missing and 83 vessels sunk in 2018 [6]. The European Maritime Safety Agency (EMSA) also reported a total of 230 vessel losses during 2011–2018 [7].

The container ship grounding accident that happened in the Suez Canal on March 23, 2021 prompted the public to rethink safety and emergency issues in the maritime industry [8]. Human errors, technical failures, and mechanical breakdowns are highlighted as the main root causes of maritime accidents [9]. In addition, the absence of effective emergency management also contributes to unexpected loss of life and damage, all of which impede the sustainable development of the maritime industry. Therefore, the present study sought to systemically review the work conducted to clear these obstacles impeding the sustainable development of the maritime industry. Several similar reviews have been conducted by scholars [10–19], mainly focused on the theme of risk analysis, methodologies, or factors analysis, and these review articles are summarized in Table 1. Unlike previous literature reviews concentrating on the analysis of accident causes and risk assessment to prevent the reoccurrence of maritime accidents, in the present study, we focused on the thematic coverage of safety risk analyses and emergency issues in maritime transportation aspects, such as shipping lanes, maritime supply chains, and maritime operations. Solutions for these issues are essential for maritime industry continuity and handling unforeseen disruptions, such as natural disasters, heavy maritime casualties, and terrorist attacks. The primary significance of this study was to assess the state of existing knowledge on maritime transportation safety management and to suggest future research perspectives, which might facilitate scholars and practitioners in promoting the sustainable development of the maritime industry.

Table 1. Review articles related to maritime safety in recent years (2012–2023).

Publication	Research Theme
[20]	Risk assessment models
[16]	Risk analysis
[11]	Risk analysis
[19]	Expert elicitation and BN modeling
[21]	Maritime transport policy
[10]	Fire and explosion accidents
[14]	Models and computational algorithms
[22]	Marine fuels
[23]	Navigation data visualization
[24]	Cyber risk perception
[18]	Human and organizational factors analysis
[15]	Human factors and safe performance
[25]	Resilience
[13]	Human reliability analysis
[12]	Risk assessment methods

The remainder of this study is organized as follows: Section 2 presents the data source and methodology. Section 3 shows the results of the descriptive statistical analysis. The network-based bibliometric analysis is described in Section 4. Section 5 summarizes the methodologies/technologies employed for maritime safety and emergency studies. A discussion on potential research perspectives is provided in Section 6, and finally, conclusions are drawn in Section 7.

2. Data Source and Bibliometric Methods

2.1. Data Source

The scientific publication data used in this study were collected from the Web of Science (WOS) core collection database, one of the most comprehensive multi-disciplinary content search platforms for academic research. Only journal articles were included in this study. The determination process for this data source is shown in Figure 1.

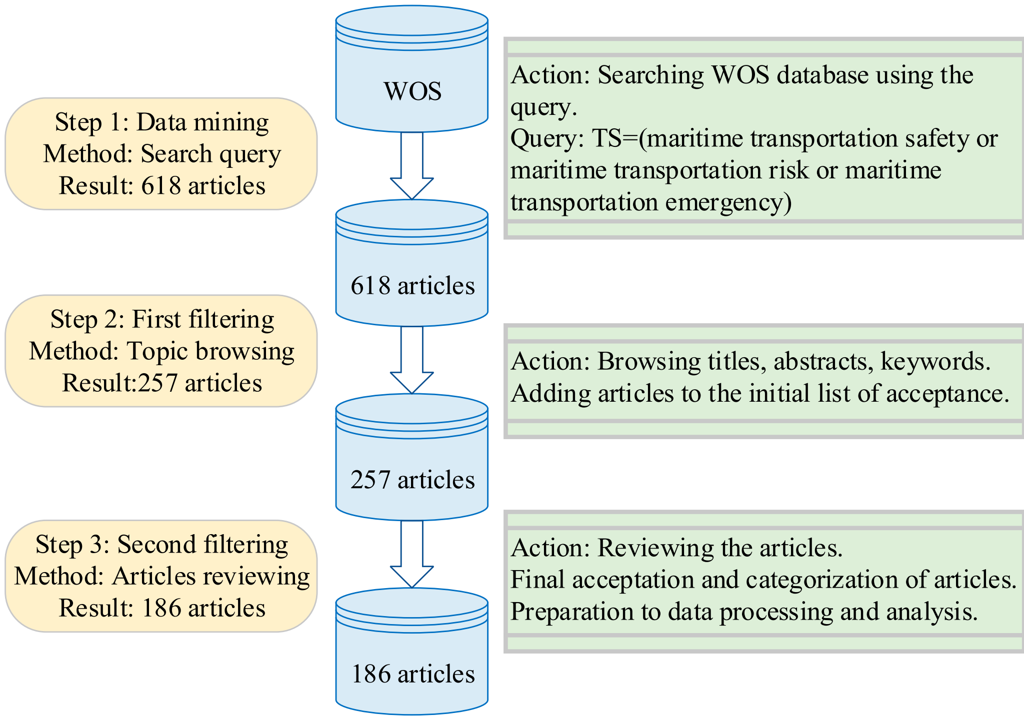

Figure 1. Literature retrieval process.

Step 1—Obtaining the original dataset by using data mining. According to the discussion in Section 1, the safety issues involved in maritime transportation can be interpreted from the aspects of risk analysis and emergency management; therefore, "maritime transportation safety" or "maritime transportation risk" or "maritime transportation emergency" was selected as the search query to identify the records from the database. In the present study, the two WOS core collections of *Science Citation Index Expanded (SCIE)* and *Social Sciences Citation Index (SSCI)* were selected as the database. The time span was set from 1 January 2011 to 31 December 2022, and the precise search was set as disabled. Finally, a total of 618 journal articles were identified by implementing the search query.

Step 2—Preparing the data sample by the first filtering. All of the articles retrieved from WOS in Step 1 were investigated by focusing on the title, abstract, and keywords, the results of which led to the development of a new dataset for further filtering. According to the research purpose mentioned in Section 1, an article was considered relevant for further analysis if any aspects of maritime transportation safety management were investigated, such as maritime transportation risk analysis/assessment, maritime transportation safety management/strategies, and maritime transportation emergency management/response. As a result, 257 articles were identified.

Step 3—Determining the final data sample to be analyzed by the second filtering. All of the articles obtained in Step 2 were reviewed one by one to verify their conformance within the scope of this study. Finally, 186 articles were selected for the final literature review. Additionally, all of the collected articles were categorized on the basis of their research perspective, as presented in Table 2. In some cases, an article was assigned to more than one category. For instance, those articles concentrating on emergency decision analysis by means of maritime network modeling were assigned to the categories of maritime network/system and decision analysis.

Table 2. Categories of the studies in terms of maritime transportation safety management.

Category	Description
Maritime network/system	Assessment of the resilience of maritime transportation networks; exploring the vulnerability of transportation networks; maritime transportation system risk assessment and safety analysis; designing maritime safety management systems.
Polar navigation	Decision making on process risk of Arctic route; optimizing the management for Arctic mass rescue events; interfering ship navigation process safety in Arctic waters.
Intelligent/unmanned navigation	Assessment of the potential impact of unmanned vessels; risk assessment of the operations of maritime autonomous ships.
Marine environment	Analyzing oil spill risk assessments; predicting the oil spill's trajectory; studying optimal scheduling of emergency resources for maritime oil spills; causes of oil spill pollution; providing a scientific basis for targeted strategic oil spill emergency planning.
Accident causation analysis	Exploring the causal factors of marine accidents; evaluation of the prediction of marine accident consequences; human error assessment.
Port/supply chain	Improving the resilience strategies of ports/supply chain; managing port operational efficiency.
Decision analysis	Optimization of maritime emergency material allocation; studies on emergency evacuation management; improving emergency management operations.
Other	All other studies not specified above.

2.2. Bibliometric Methods

Early discussion of bibliometrics began in the 1950s [26], during which bibliometrics were used to study or measure academic research through the scientific publications stored or indexed in large bibliographic databases [27]. Total scientific output, number of citations, keywords, authors, and institutions are typical indicators. The results of such analysis can be visualized in various forms, such as maps or networks, to describe datasets in a clear way. Such mapping analysis of academic research is becoming a popular method to gain insight into the field of scientific activity through the representation of bibliometric indicators [28]. Its popularity mainly lies in the advancement, availability, and accessibility of bibliometric software, such as CiteSpace 5.5.R2 and VOSviewer 1.6.13 [29]. Bibliometric software can be used to analyze data samples in a very pragmatic way, which has thus increased the academic interest in bibliometric analysis. Furthermore, with the help of software analysis, the bibliometric methodology has been widely applied in various fields, such as medicine [30], agriculture [31], business strategy [32], and marine development [33,34].

Generally, bibliometric analysis is widely used to characterize the internal structural relationship of the collected articles by means of: (1) obtaining changes in the number of articles in the field over the years; (2) showing the cooperative relationship of countries, institutions, or authors and visualizing the research team throughout the circle of research; (3) locating high-impact journals, institutions, and authors and finding the most influential authors, research institutions, or journals; (4) grasping popular research topics, gathering statistics on high-frequency keywords over the years, and finding research hotspots and development trend; (5) analyzing the citation relationship network, sorting the research development context, and assisting literature reviews. In the present study, bibliometric analysis was used to comprehensively understand the research hotspots and development trends of maritime transportation safety and emergency management from a global perspective.

3. Descriptive Statistical Analysis

3.1. Publication and Citation Distribution Analysis

Citation and publication metrics can be used to demonstrate the importance of maritime safety and emergency research. Figure 2 illustrates information about the development of the number of total publications and citations. The peak number of citations can be observed in 2021, with 654 citations. New publications need time to catch up regarding the number of citations, so it is natural that the number of citations should decrease after a period of time. Meanwhile, the evolution of annual publications shows a gradual increasing trend, which indicates that the sustainable development of maritime transportation has received increasing academic attention. International organizations, such as IMO and the International Association of Lighthouse Authorities (IALA), have put forward suggestions on the use of specific risk analysis and management tools [11], which may be an explanation for the significant increase in production.

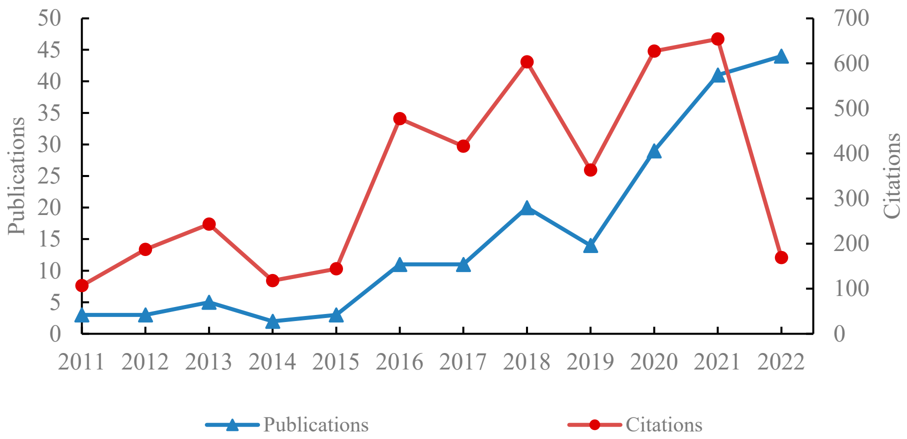

Figure 2. Number of publications and citations.

Detailed information of each considered category is presented in Figure 3 in terms of citations, publications, publication years, and affiliations. Each radar plot represents a different aspect of the conducted analysis. According to Figure 3, the maximum citation frequency was observed in the “Other” category. In terms of publications, the "Maritime network/system” category had the highest number of articles published, with 41 articles. With regard to the year of publication, the maritime transportation network and decision analysis topics were analyzed relatively early. Additionally, in this study, more than 80% of all of the articles were contributed by research universities.

3.2. Country and Institution Distribution Analysis

A total of 49 countries contributed to maritime transportation safety and emergency management over the time span of the study, and the top 10 countries with the highest scientific productions from 2011 to 2022 are presented in Figure 4, including 5 European countries, 2 Asian countries, 2 North American countries, and 1 Oceanian country. Furthermore, as seen in Figure 4, the most highly published articles were written by scholars from China, England, and Finland. Of the articles, 44% were published by Chinese scholars. China has been paying attention to research in the field of maritime transportation safety and emergency management since 2007 [35]. Within China, the top three productive universities were Dalian Maritime University (19%), Wuhan University Technology (14%), and Shanghai Maritime University (10%). Meanwhile, 14% of the articles were from England, ranking second, with Liverpool John Moores University (12%) and University Oxford (2%) being the main research institutions regarding safety and emergency management for maritime transportation. Lastly, 12% of articles came from Finland, ranking third, with Aalto University (9%) dominating in research intensity. Additionally, Turkey, Canada, the USA, Singapore, Poland, Australia, and Portugal contributed to the sustainable development of maritime transportation in the aspects of safety and emergency management.

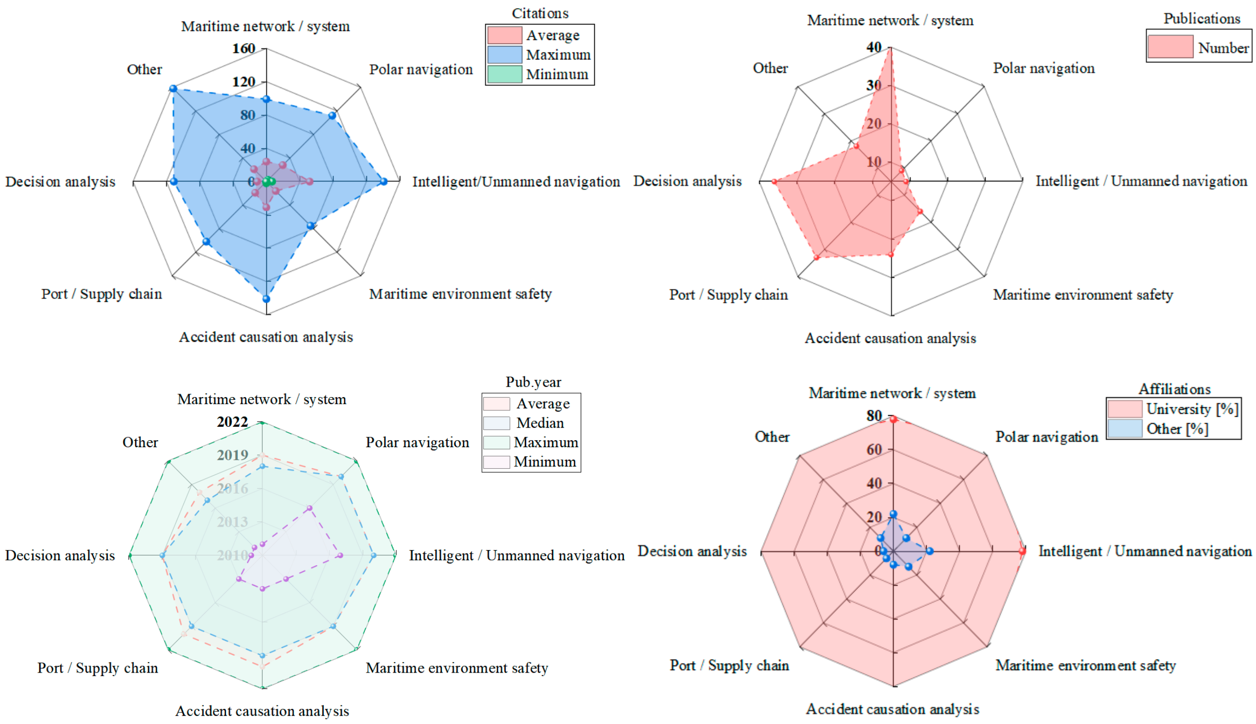

Figure 3. Radar plots for the citations, publications, publication years, and affiliations for each category.

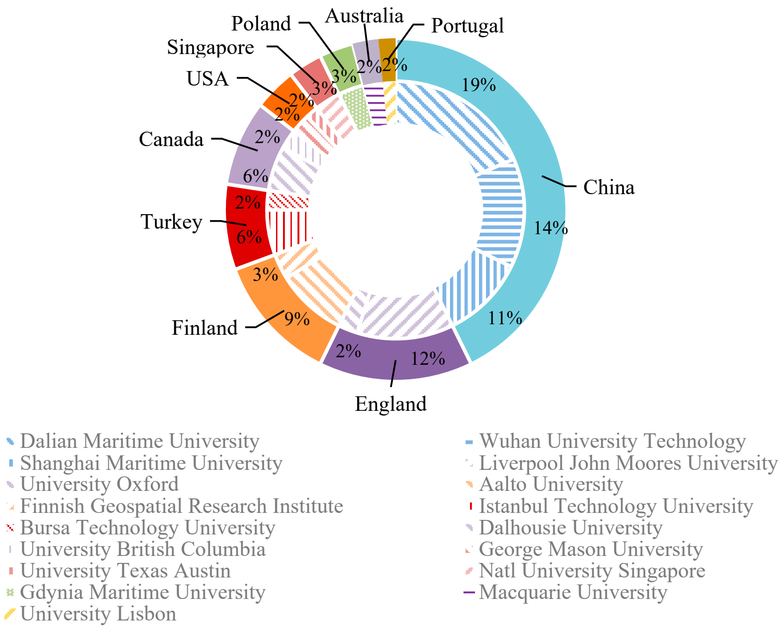

Figure 4. Counties and affiliations on WOS by number of articles published.

A co-operation diagram of the affiliated institutions distributed by countries is shown in Figure 5. According to the co-authorship among the different institutions, it is worth noting that Dalian Maritime University cooperated with scholars from Liverpool John Moores University and Shanghai Maritime University. Wuhan University of Technology engaged in academic co-operation with Liverpool John Moores University, Alto University, and Dalhousie University. Overall, this highlights that researchers actively collaborate with cross-regional institutions in maritime transportation safety and emergency management.

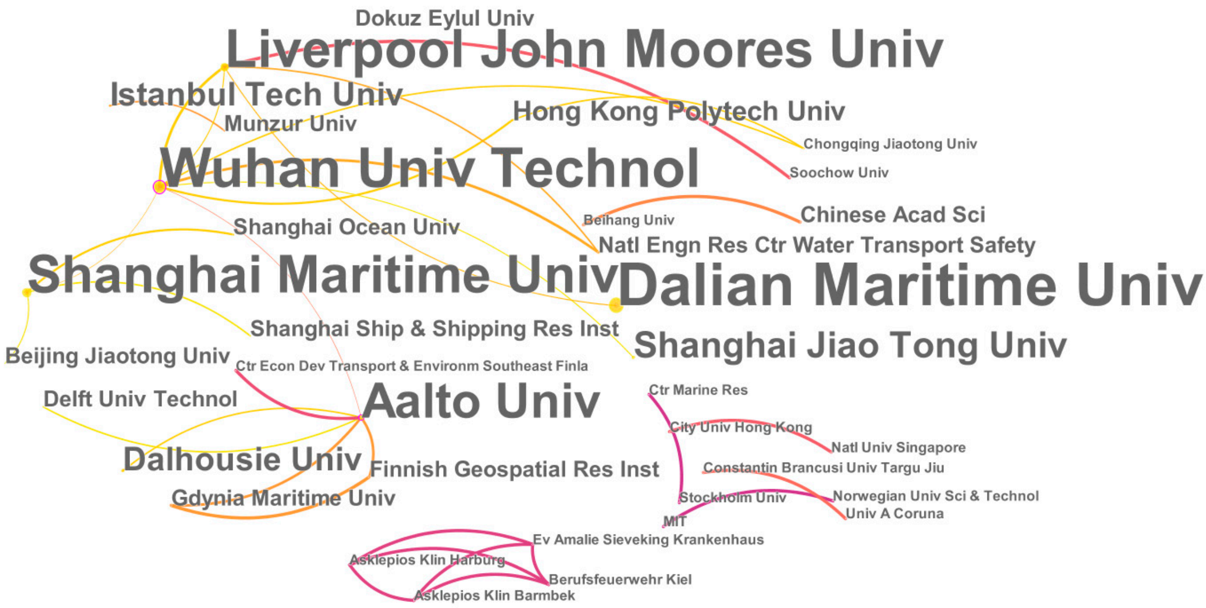

Figure 5. Co-operation between research institutions.

3.3. Influential Journal and Study Analysis

3.3.1. Influential Journal Analysis

In the field of maritime transportation safety and emergency management, a total of 94 journals published relevant articles, of which the journal with the highest citations was *Reliability Engineering & System Safety,* with 697 citations, as shown in Figure 6. Focusing on shipping logistics and policy, *Ocean Engineering* was the second most-cited journal, with 582 citations, indicating its high influence for maritime transportation safety and emergency management. Subsequently, we noticed that *Transportation Research Part E-logistics and Transportation Review, Safety Science*, and *Risk Analysis* had higher citation frequencies. These journals have made important academic contributions to the development of maritime transportation safety and emergency management and are widely recognized as high-quality journals related to maritime transportation safety and emergency issues. In addition, journals, such as *Maritime Policy & Management, Ocean & Coastal Management, Ocean Engineering,* and *Reliability Engineering & System Safety,* mainly focus on addressing maritime accidents (e.g., oil spills and collisions), resilience assessment [36], and vulnerability analysis [37] with quantitative methods, such as DBN and Markov chain [38–41].

The top 10 journals with the highest number of publications are presented in Figure 7. According to Figure 7, *Ocean Engineering* ranks first, with 21 publications. In second position is *Reliability Engineering & System Safety,* with 16 publications, followed by *Maritime Policy & Management*. The number of articles in the top three journals accounts for 26.34% of the total number of articles. The majority of these journals are related to transportation, operations research, and management science, highlighting the theme of maritime transportation safety and emergency management.

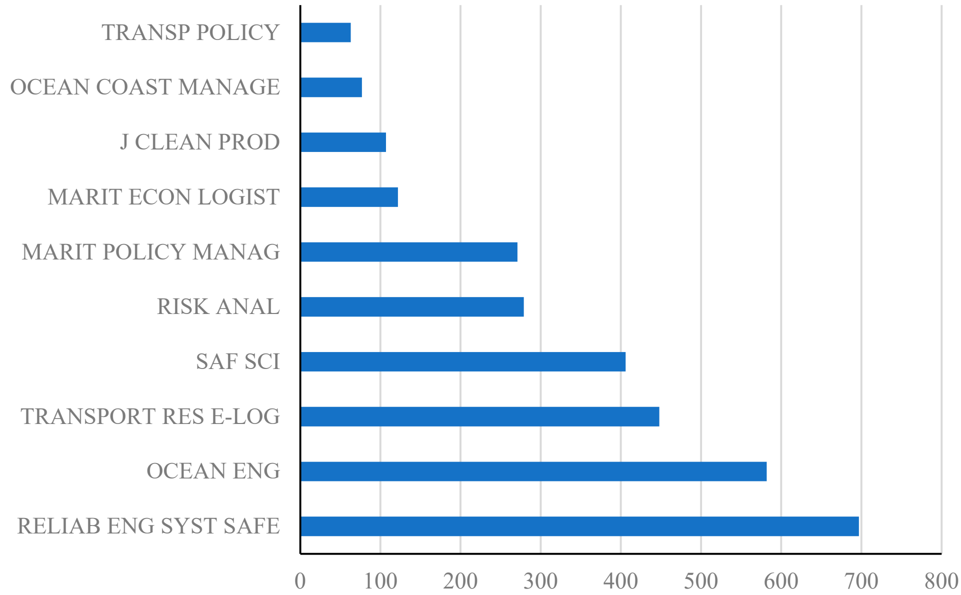

Figure 6. Top 10 journals in terms of global citations.

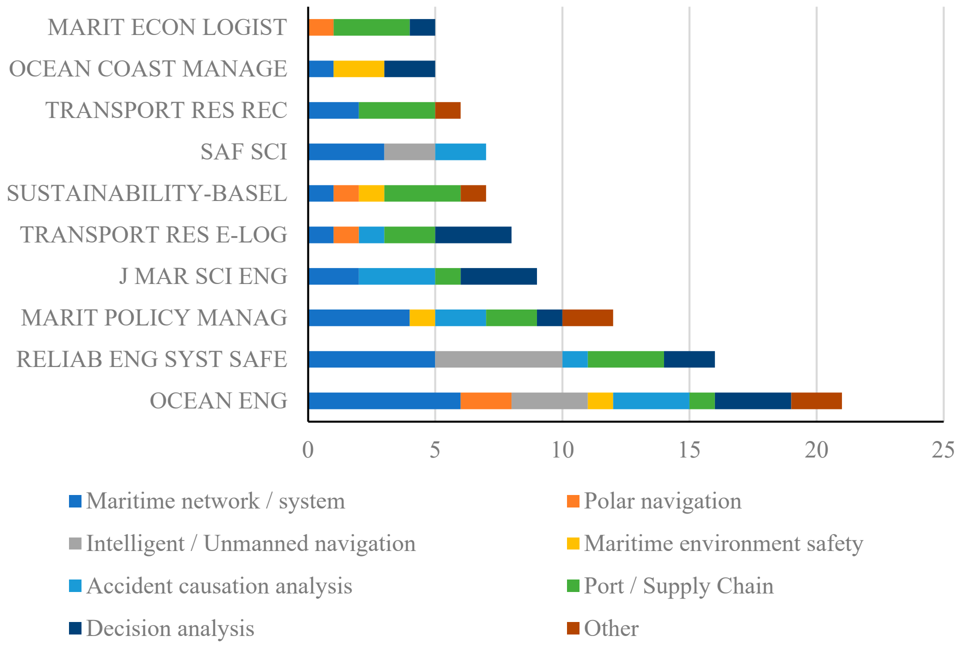

Figure 7. Number of publications by journal.

3.3.2. Influential Scholar Analysis

A total of 674 authors were included in 186 articles collected in this study. Core authors can conduct continuous research and have certain influence in their respective research field, and the number of publications is the most intuitive indicator. The price formula is considered a quantitative standard for selecting core authors, as shown in Equation (1):

$$M = 0.749\sqrt{N_{\max}} \tag{1}$$

where $N_{\max}$ represents the number of articles published by the most productive author during a study period of time; M denotes the minimum number of articles published by the core author. According to Equation (1), the core author published no less than three articles. The authors' production over time is depicted in Figure 8. The color code used denotes an average number of citations aggregated for articles published in a given year.

The core authors in the field of maritime safety and emergency management published 67 articles in total, accounting for 36.02% of the 186 publications. It can also be seen that Yang ZaiLi conducted maritime safety and emergency management research in early 2013 [42]. The increase in the number of articles published by core authors remained consistent with the overall trend in the number of published articles in the analyzed topic. It is noted that some authors interrupted their research on maritime safety and emergency management; however, they returned to this study field after a few years. According to the query used in the WOS database and collected dataset, Lv Jing and Fu Shanshan had a four-year gap between their articles related to maritime safety and emergency management. Meanwhile, we found that these core authors frequently used the BN and CN methods to study maritime transportation safety issues [43–46] and mainly focused on oil spill problems [47]. In addition, a few authors were instrumental in studying maritime resilience and vulnerability assessment [48,49].

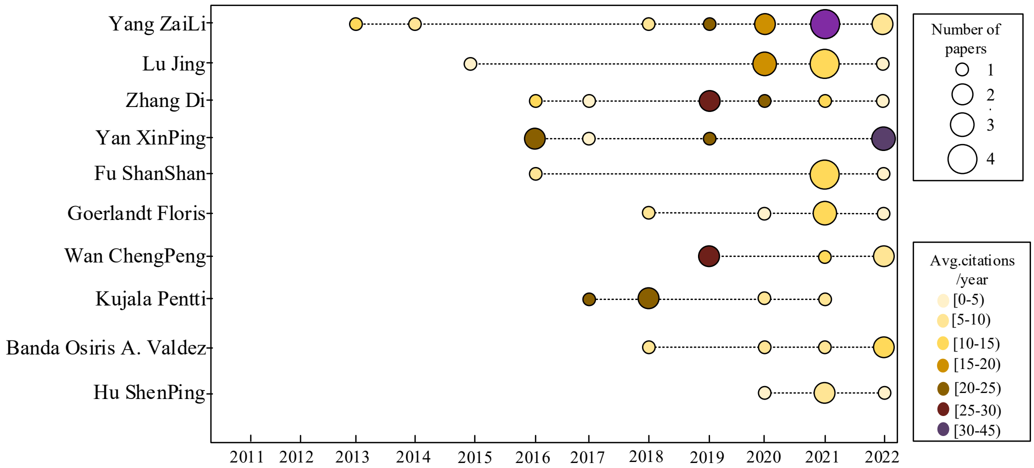

Figure 8. Top authors' production over time with the number of citations in a given year.

3.3.3. Highly Cited Articles

Citation frequency is the most commonly used indicator to measure the quality of literature, and Table 3 shows the top 10 citation frequency rankings. The highly cited articles related to maritime transportation safety and emergency management were mainly concentrated in journals, such as *Transportation Research Part E-logistics And Transportation Review, Risk Analysis*, and *Safety Science*. A total of 10 highly cited articles were cited 1150 times. Specifically, "An Overview of Maritime Waterway Quantitative Risk Assessment Models" published in *Risk Analysis* [20] had the highest number of citations (i.e., 158), and an average citation rate of 15 times per year. In addition, "Towards the assessment of potential impact of unmanned vessels on maritime transportation safety" was ranked as the second citation, in which the Human Factors Analysis and Classification System (HFACS) was adopted to study maritime accident causations (e.g., collision and grounding) [50]. Furthermore, "Marine transportation risk assessment using Bayesian Network: Application to Arctic waters" attracted much attention in terms of understanding the risk of maritime accidents [51]. These highly cited articles have laid the foundation for subsequent scholarly research in the maritime transportation safety and emergency management.

Table 3. Top 10 articles in terms of global citations.

Article	Source	Total Citations	CY
An Overview of Maritime Waterway Quantitative Risk Assessment Models [20]	*Risk Analysis*	158	14
Towards the assessment of potential impact of unmanned vessels on maritime transportation safety [50]	*Reliability Engineering & System Safety*	141	21
A Human and Organisational Factors (HOFs) analysis method for marine casualties using HFACS-Maritime Accidents (HFACS-MA) [42]	*Safety Science*	141	13
Marine transportation risk assessment using Bayesian Network: Application to Arctic waters [51]	*Ocean Engineering*	112	20
Multi-objective decision support to enhance environmental sustainability in maritime shipping: A review and future directions [52]	*Transportation Research Part E-logistics And Transportation Review*	111	13
An advanced fuzzy Bayesian-based FMEA approach for assessing maritime supply chain risks [53]	*Transportation Research Part E-logistics And Transportation Review*	105	23
Disruptions and resilience in global container shipping and ports: the COVID-19 pandemic versus the 2008–2009 financial crisis [54]	*Maritime Economics & Logistics*	102	39
A quality function deployment approach to improve maritime supply chain resilience [55]	*Transportation Research Part E-logistics And Transportation Review*	100	13
Maritime Transportation Risk Assessment of Tianjin Port with Bayesian Belief Networks [56]	*Risk Analysis*	99	13
A marine accident analysing model to evaluate potential operational causes in cargo ships [57]	*Safety Science*	81	12

CY: Citations per article per year on average.

4. Network-Based Bibliometric Analysis

4.1. Keyword Analysis

The keywords that appear in the titles and abstracts of scientific articles are important descriptions of the key contents. In this section, keywords were extracted from the titles and abstracts of the scientific publications from the WOS dataset using an automatic keyword recognition method [58], and a keyword map was visualized by using VOSviewer [59]. In Figure 9, a keyword co-occurrence diagram depicts only those keywords that appeared in at least three different articles, as a threshold was adopted for its visualization. A simple descriptive statistical analysis showed that the frequency distribution of keywords was very uneven, with only a few keywords appearing with high frequency and many keywords appearing with relatively low frequency. For example, there were only nine keywords that occurred at least 10 times in the considered dataset. These keywords were "resilience" (38), "model" (32), "framework" (27), "vulnerability" (24), "Bayesian network" (16), "optimization" (16), "impact" (14), "risk" (12), and "safety" (12).

Keyword burst citation analysis can be used to detect whether a specific research topic is hot or not. Generally, notable increases in a research field are characterized by citation bursts in publications. Keyword citation bursts can show the emerging topics in the maritime safety and emergency management field. In our study, in order to better understand the research trends of maritime transportation safety and emergency management, the evolution of keyword hotspots was analyzed from the perspective of keyword emergence. In the past 12 years, there were 17 different bursting keywords in maritime safety and emergency management publications. Table 4 lists these 17 bursting keywords with their strength and time span, as keyword emergence is typically divided into five phases by time.

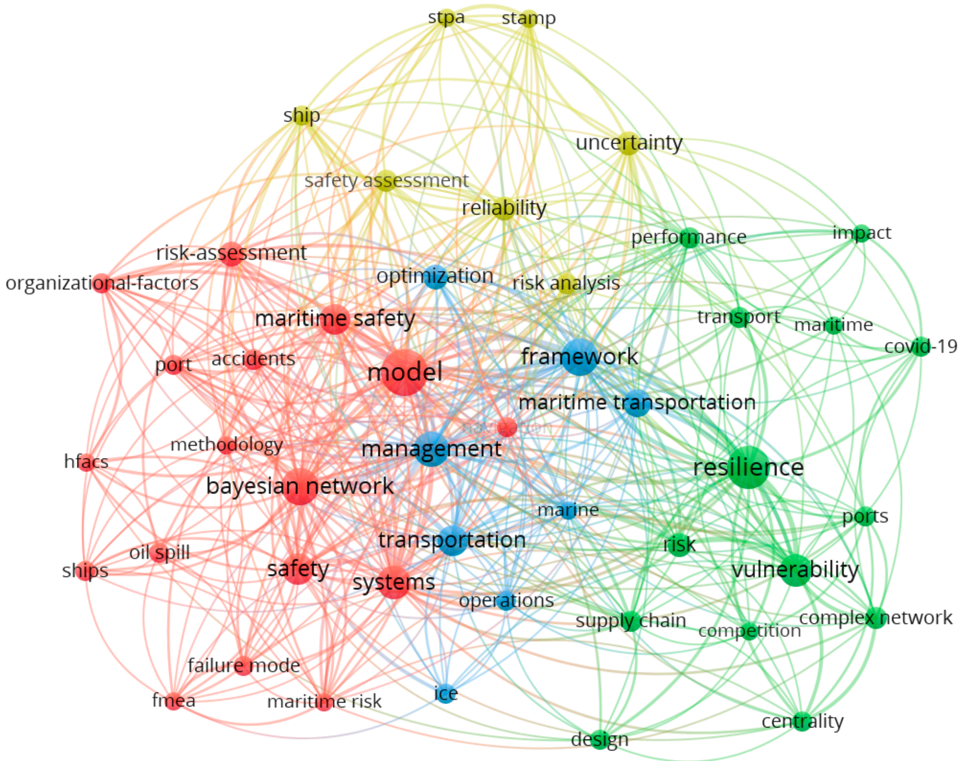

Figure 9. Co-operation between research topics.

Table 4. Top 17 keywords with the strongest citation bursts.

Keywords	Strength	Start	End	2011 to 2022
Accident	3.0334	2016	2017	
Maritime transportation	1.8375	2017	2018	
Transportation	1.3173	2018	2019	
Optimization	0.5586	2018	2019	
Disaster	2.2001	2018	2019	
Network	1.4665	2018	2019	
Vulnerability	0.3527	2018	2019	
Emergency evacuation	2.2001	2018	2019	
Port	0.731	2019	2020	
Management	1.3672	2019	2020	
Operation	1.3958	2020	2021	
Maritime accident	1.1139	2020	2021	
Risk	1.4033	2020	2021	
BN	3.1174	2020	2021	
Recovery	1.1139	2020	2021	
Sustainability	0.8203	2021	2022	
Maritime safety	0.8203	2021	2022	

(1) The first stage (2016–2018): Mainly focused on maritime accident causation analysis. The keywords that emerged were accident and maritime transportation.

(2) The second stage (2018–2019): The study of maritime transportation safety and emergency management boomed. To prevent any disasters caused by activities (e.g., grounding and oil spills), emergency evacuation under different scenarios was studied by using mathematical modeling and optimization methods. Maritime transportation network resilience and maritime transportation vulnerability identification were also an-

alyzed. The main keywords that emerged were transportation, optimization, network, vulnerability, and emergency evacuation.

(3) The third stage (2019–2020): Mainly focused on the maritime port network resilience, the risks of port disruptions, and maritime transportation management strategies. The main keywords that emerged were port and management.

(4) The fourth stage (2020–2021): Mostly focused on the risk evaluation and recovery strategies of maritime transport systems. The main keywords that emerged were operation, maritime accident, risk, BN, and recovery.

(5) The fifth stage (2021–2022): Mainly focused on maritime transportation safety and sustainability. In this stage, researchers analyzed the safety of maritime transportation from different perspectives, such as the development of port vulnerability assessment (PVA) frameworks and the proposal of optimal resilience models in maritime transportation systems. The main keywords that emerged were sustainability and maritime safety.

4.2. Co-Cited Analysis

4.2.1. Journal Co-Citations

The co-citation frequency of journals is the main indicator for measuring the attractiveness of academic journals. Therefore, we further analyzed journal sources by drawing a network map of co-citations with the WOSviewer application, where the relationship between two different publications could be assessed based on the number of articles citing both journals. This helped to visualize the inter-relationships between the sources of the journal, as shown in Figure 10, in which the link strength is the frequency with which two journals appear in one publication simultaneously. The most relevant sources were *Reliability Engineering & System Safety*, *Safety Science,* and *Maritime policy & Management*, which were closely linked based on the most citations. We noticed that the cluster centered by *Reliability Engineering & System Safety* was the largest, and its number of published articles ranked second, with 16 articles. A similar situation was also applicable to *Risk analysis* and *Accident Analysis & Prevention*, both of which had common citation characteristics. In addition, there was a large number of co-citations in other journals, such as *Expert System with Applications* and *Computers & Industrial Engineering*, making the field of maritime transportation safety and emergency management comprehensive and interdisciplinary.

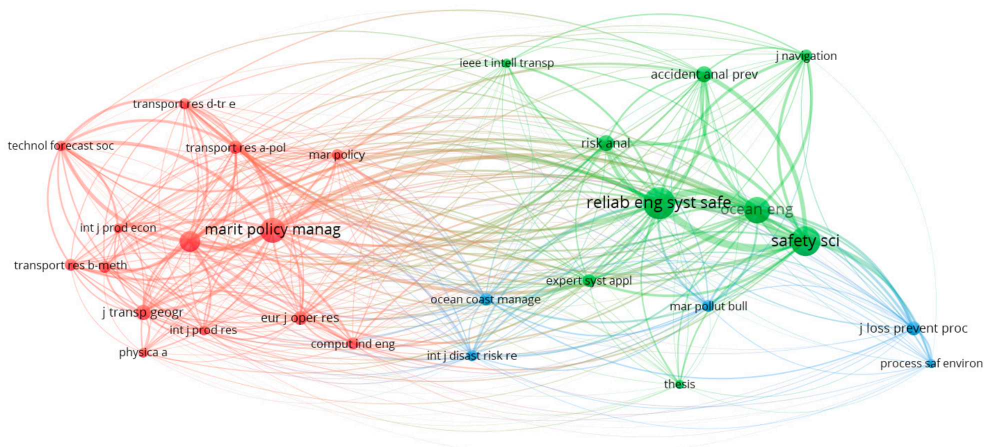

Figure 10. Co-citation network of journals cited by publications.

4.2.2. Article Co-Citations

Two articles establish a co-citation relationship when they appear in the references of another article simultaneously. As a result, a co-citation map could be established by using WOSviewer 1.6.13, which is illustrated in Figure 11. This figure shows the minimum number of a cited reference to be at least 10 times; the size of the node represents the citation frequency, and the line between two nodes indicates that they have been cited at least once. In general, if two articles establish a co-citation relationship, they are more or less similar.

It can be seen that the published articles in the field of maritime transportation safety and emergency management can be grouped into three categories.

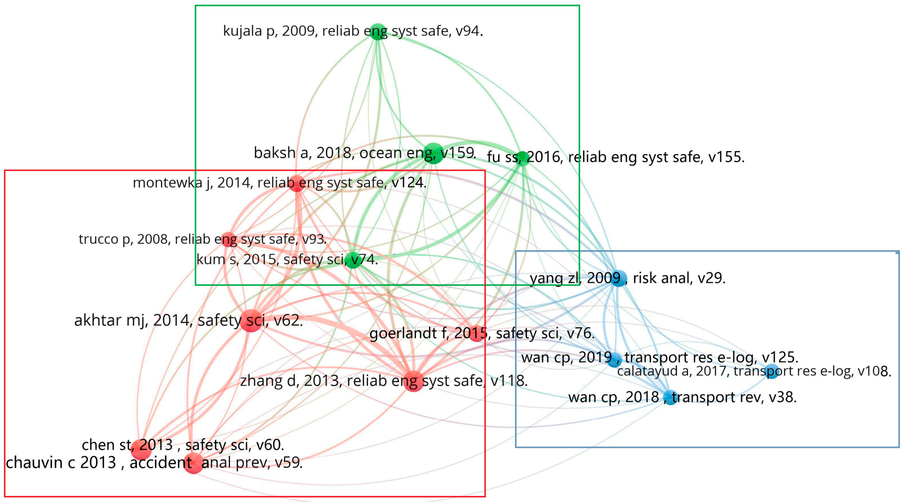

Figure 11. Co-citation network of references cited by publications.

Green: Highly co-cited articles mainly analyzing the possibility, risk, and cause of maritime accidents, such as collision, foundering, and grounding [51,60–62]. It is noteworthy that such studies were mainly focused on Arctic waters.

Red: Highly co-cited articles mainly studying the risk quantification [63–65] and human and organizational factor (HOF) analysis [42,66–68] for maritime transportation systems.

Blue: Highly co-citated articles mostly developing fuzzy logic methods to analyze maritime security assessments [53,69]. In addition, maritime transportation vulnerability was described by Calatayud et al. [70] from a multiplex network perspective.

4.2.3. Author Co-Citations

Author co-citation analysis is another interesting topic. We set the threshold as 15, and 36 authors were selected. The results were visualized by using WOSviewer 1.6.13, where a node represents an author and a line is established when two authors are cited in one article. The distance between two nodes reflects the degree of similarity to the authors' field of study. The most influential authors can be observed in Figure 12. It should be noted that there were some articles that cited the data provided by institutes like the IMO and the UNCTAD; in these cases, the institutes that provided the data were regarded as authors. According to the results, Goerlandt, Montewka, Yang, Akyuz, IMO, Wu, Hollnagel, Zhang, Banda, and Ducruet were the most-co-cited authors.

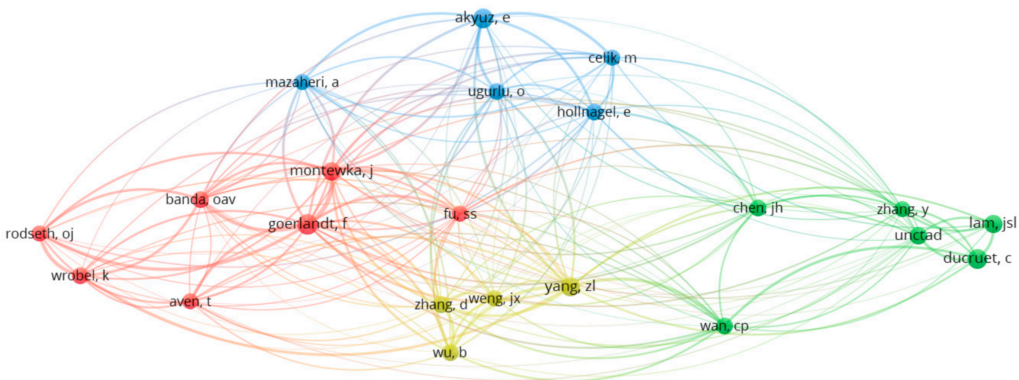

Figure 12. Mapping of the author co-citations.

The first category represents the authors in the field of human factors analysis, including Akyuz, Hollnagel, and Celik. Specifically, to achieve maritime safety, Akyuz and Celik proposed the HFACS combined with a cognitive map (CM) in maritime accident analysis [71], as well as human error assessment and reduction technique (HEART) [72] methods, which were developed as a marine-specific approach to quantify human error. Hollnagel focused on evaluating the human factors based on the FRAM approach [73].

The second category represents the authors in the field of risk influencing factors analysis of Arctic waters, including Zhang, Fu, and Khan. Specifically, Zhang and Fu mainly used BN [74] and the analytical hierarchy process (AHP) [75] to analyze the potential risk factors in Arctic shipping. As a co-author, Khan also adopted DBN [76] and BN [77] to identify and classify contributing risk factors for Arctic waters. Additionally, an updated Nagel–Schrekenberg (NaSch) model of Arctic marine convoy traffic integrated with a BN-based probabilistic approach was used to predict the maximum waterway density for the safe flow of traffic and the collision probability during a convoy [78], highlighting the implementation of advanced technology as being crucial in enhancing safe navigation at sea.

The third category represents the authors in the field of safety management, including Goerlandt, Montewka, and Banda. Specifically, Goerlandt was the most-co-cited author in the field of maritime transportation and mainly engaged in research on maritime risk analysis and management, involving oil spill preparedness, planning, and development of tools for maritime accidents. As the co-authors, Goerlandt and Montewka presented a review and analysis of risk definitions, perspectives, and scientific approaches to risk analysis [11], as well as applied BN modeling for probabilistic risk quantification [63]. Banda developed a formal safety assessment (FSA) to assess and manage the risk of winter navigation operations [79].

The fourth category represents the authors in the field of risk assessment and accident prevention, including Wan, Yang, and Wu. Specifically, Wan and Yang applied an advanced fuzzy Bayesian-based FMEA approach to assess maritime supply chain risks [53]. Wu developed a modified cognitive reliability and error analysis method (CREAM) for estimating the human error probability in maritime accidents [80].

The fifth category represents the authors in the field of maritime network and vulnerability analysis, including Ducruet, Zhang, and Berle. Specifically, Ducruet focused on the maritime network characteristics [81–83]. Zhang frequently used the geo-spatial techniques of kernel density estimation (KDE) to identify accident-prone sea areas [84,85]. To assess the vulnerability of maritime transportation, formal vulnerability assessment (FVA) methodology was employed by Berle et al. [86] and Berle et al. [87].

5. Methodology for Maritime Safety and Emergency Management

5.1. Overview of the Research Methods

In this study, the main research methods used in the 186 articles were identified by means of a manual review. Figure 13 illustrates an overview of the research methods used in maritime transportation safety and emergency management.

There are still traditional risk assessment methods that remain widely used, despite the emergence of new methods in recent years. The early studies in maritime accident research usually adopted very basic methods, such as interviews and surveys analysis, while recent studies often used multi-disciplinary approaches and comprehensive analyses. Many different approaches have been developed to address maritime transportation safety and emergency management problems. Recently, new methods that have appeared in maritime safety and emergency management research include STPA, cognitive reliability error analysis method (CREAM), DBN, emergency assessment-based simulation [88], probabilistic risk assessment-based simulation [89], resilience assessment-based simulation [90], and mathematical modeling and optimization methods, such as non-linear optimization and enhanced particle swarm optimization (EPSO) models [91], multi-objective particle swarm algorithm [47], and dynamic multi-objective optimization model [92]. At present, machine learning is introduced to improve maritime safety and management.

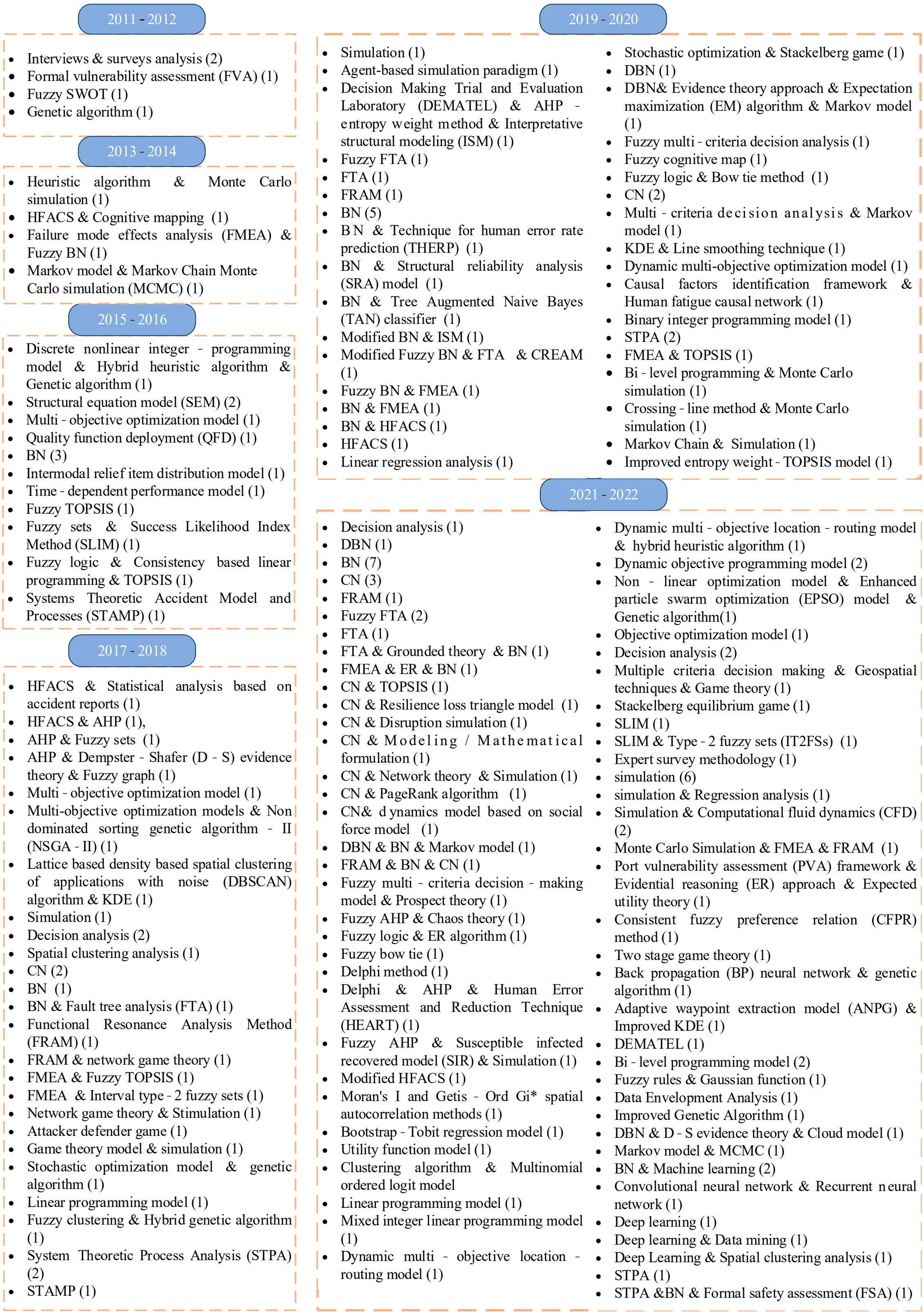

Figure 13. Overview of the methods employed in maritime safety and emergency management.

Model extension has occurred alongside the introduction of new models to this research area. Ung [93] extended the CREAM approach by incorporating BN and FTA in a fuzzy environment.

Chen et al. [42] proposed the HFACS, which has been used to identify human errors in maritime accidents. Akyuz combined the HFACS approach with the analytic hierarchy process (AHP) to evaluate potential operational causes in maritime accidents [57]. Uğurlu et al. integrated the HFACS and BN to analyze maritime collision, grounding, and sinking accidents [94]. To improve port safety, BN and FMEA were combined to assess the criticality of the hazardous events by [95]. Yuan et al. [96] combined BN and FTA to study the causal factors in emergency processes in response to fire accidents for oil gas storage. Likewise, Wang et al. [97] used BN and FTA to assess the critical risk factors in ship fire accidents. Then, Abaei et al. [98] linked BN and machine learning to analyze the resilience of unattended machinery plants in autonomous ships.

Figure 14 shows the statistics of the main research methods used in the literature. More than half of the articles used quantitative analysis to study maritime transportation safety and emergency management problems. Meanwhile, it can be seen that BN, fuzzy logic, simulation, CN, FMEA, FTA, game theory, machine learning, FRAM, HFACS, STPA, Markov model, and DBN are the most commonly used measurement methods in the field of maritime transportation safety and emergency management.

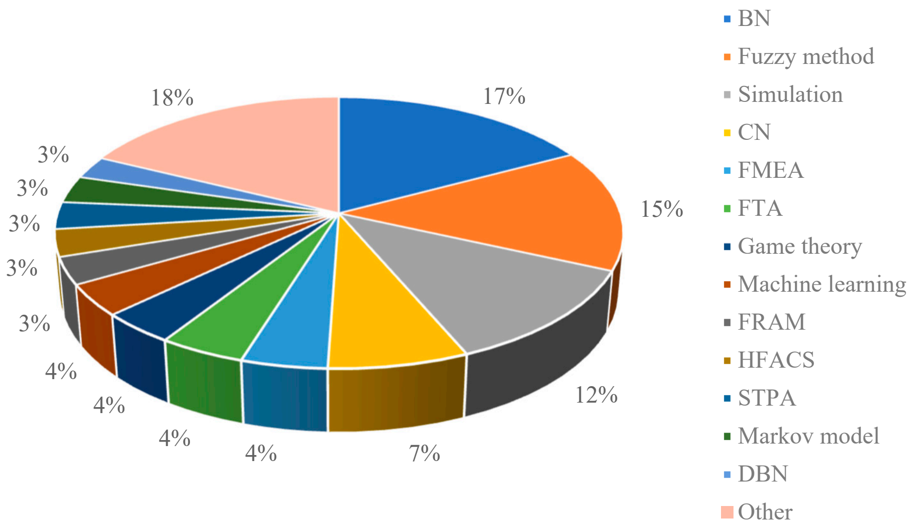

Figure 14. Statistics of the main research methods used in the literature.

According to Figure 14, the most frequently used method was the BN method. The application of the BN method mainly focuses on the following two aspects: (1) study of the causal correlation degree of factors from the accident causation theory perspective [96]; (2) risk prediction carried out using the BN model [44,53]. Maritime transportation has great uncertainty, which is affected by system complexity, environmental factors, human factors, and organizational factors [68]. BN is a suitable method for risk assessment and decision making. Furthermore, BN can replace FTA as a classification method and can take into account the joint effect of several events. This is the reason why the BN model is popular in the field of maritime transportation safety and emergency management. However, data availability is one of the biggest problems in calculating the failure rate in the maritime industry. In order to solve this limitation, fuzzy methods are widely introduced to deal with the uncertain data. Simulation is the third most frequently used tool; the risk of maritime accidents has a probabilistic attribute, and simple statistical data are not sufficient to explain and predict the risk of accidents over time. The simulation method can be used to analyze the influence of many uncertain factors. Faghih-Roohi et al. [99] combined Monte Carlo simulation and the Markov model to estimate the probability of maritime transport accidents for the first time. Huang et al. [100] adopted the Monte Carlo method to calculate the probability of a ship crossing the channel boundary. Zou and Chen [101] used Monte Carlo simulation to assess the resilience of the maritime supply chain and analyzed the impact of interruption scenarios for maritime transportation systems.

Table 5 provides a comparison of the main methodological features used in this study: (1) Quantitative—used to distinguish whether the method is quantitative or qualitative. (2) Interactivity—referring to the mechanism of interaction between the factors. (3) Interpretability—providing a specific path for the propagation of risk factors. (4) Decoupling—considering the contribution of each factor function in the case of multiple factors completing the task in a cooperative manner. (5) Memorable—considering the impact of task completion results on other subsequent tasks. Not all risk behaviors or states will necessarily contribute to serious consequences, and only when certain conditions are met will the next stage of risk events or accidents be triggered. (6) Sequential—considering the sequence of events. (7) Scalability—the ability to combine with other methods. (8) Extensibility—the ability to handle large-scale parameters.

Table 5. Comparison of the main methodological features used in the literature.

Methods	Quantitative	Interactivity	Interpretability	Decoupling	Memorable	Sequential	Scalability	Extendibility
BN [97]	✓	✓	✓			✓	✓	
Fuzzy method [93]	✓						✓	
Simulation [102]	✓	✓	✓	✓	✓		✓	✓
CN [49]	✓	✓	✓	✓			✓	✓
FMEA [99]	✓		✓				✓	
FTA [93]	✓		✓			✓	✓	
Game theory [103]	✓	✓	✓				✓	
Machine learning [98]	✓	✓			✓		✓	✓
FRAM [89]		✓	✓	✓			✓	
HFACS [94]							✓	
STPA [104]		✓	✓				✓	
Markov model [44]	✓	✓	✓				✓	
DBN [44]	✓	✓	✓			✓	✓	

5.2. The Progressive Trend of Research Methods

Figure 15 illustrates the progressive trend of the primary methods and models utilized in maritime transportation safety and emergency management between 2011 and 2022. The advancement of technology has expanded the application scope and enhanced their accuracy in various scenarios. Between 2011 and 2013, statistical analysis and framework-based analysis were the predominant methods employed in maritime transportation safety and emergency management. Traditional risk analysis techniques, such as FVA, SWOT, and HFACS, were widely applied during this period. Heuristic algorithms were used to solve complex problems by iteratively exploring and evaluating a large search space. From 2014 to 2016, fuzzy BN, Markov model, MCMC, mathematical modeling, and STAMP were employed to identify the maritime transportation system risk. From 2017 to 2019, CN, cluster analysis, multi-objective optimization models, simulation, game theory, STPA, and ISM were introduced to study maritime transportation safety and emergency management issues. Human reliability analysis methods, such as CREAM and THERP, were employed to identify human errors in maritime risk. More specific and detailed research methods were used to evaluate maritime safety and emergency management. From 2020 to 2022, methods, such as DBN and dynamic programming models, were utilized to assess risks and optimized paths in the maritime safety and emergency management field. Additionally, the development of research methods has facilitated the application of machine learning algorithms, such as BP neural networks, convolutional neural networks, and recurrent neural networks in maritime safety and emergency management.

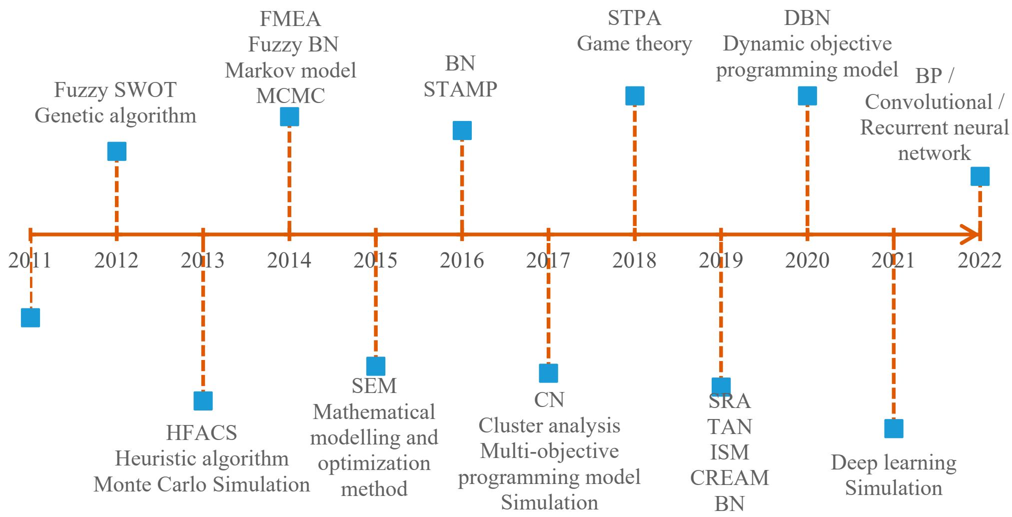

Figure 15. The progressive trend of research methods.

5.3. Spatial Interaction Visualization of Research Methods

Figure 16 shows the spatial interaction visualization of research methods. Let graph $G\ (V,\ E,\ W)$ be the representation of the main research method network. In this graph, V is the set of nodes representing methods, E is the set of edges representing the linking between methods, and W is the weight of edge. Graph G is represented as a weighted adjacency matrix **A**, whose elements are $a_{ij} = w_{ij}$. If link $(i,j) \in E, i,j \in V, a_{ij} = w_{ij}$, where w_{ij} indicates the number of methods connecting method i and method j; otherwise, $a_{ij}= 0$. Finally, the spatial interaction visualization of main research methods is connected in a CN, as given Figure 16.

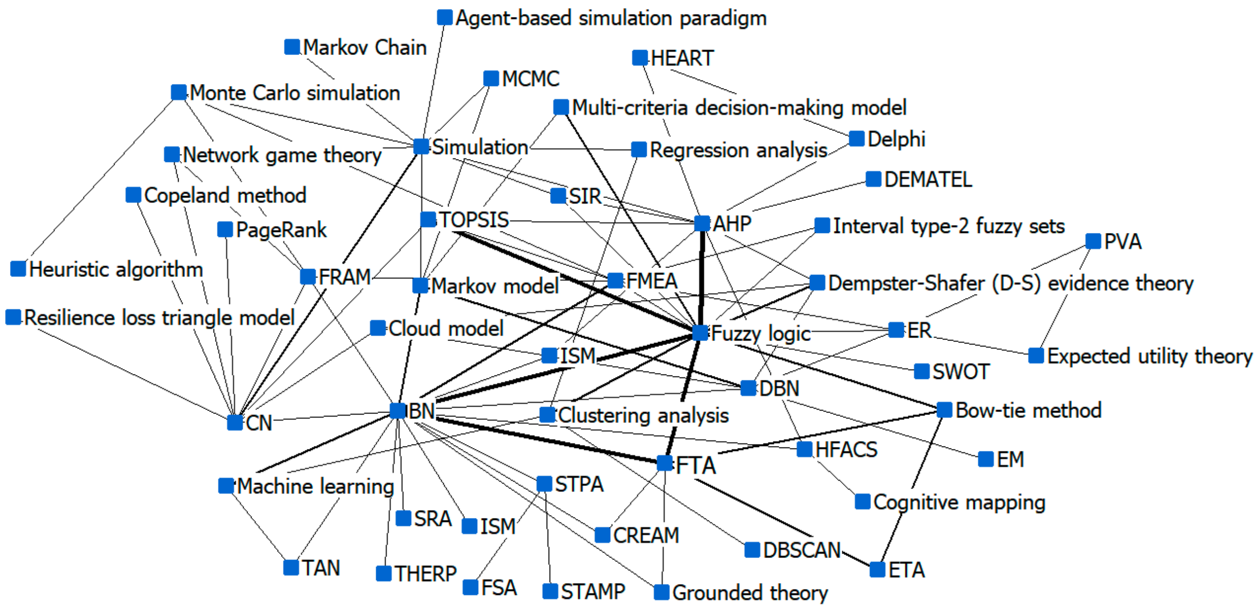

Figure 16. Spatial interaction visualization of the methods and models used in the literature.

Fuzzy logic can deal with uncertainty and vagueness and can be integrated with other methods to handle imprecise inputs. Fuzzy set analysis has been widely used together with methods, such as FTA, SWOT, FMEA, ER, bow-tie method, BN, and AHP. For example, Zaib et al. [105] analyzed human error using a fuzzy FTA. Jiang et al. [48] used the fuzzy evidential reasoning (ER) algorithm to estimate the vulnerability of straits or canals in maritime transportation. Furthermore, Fuzzy TOPSIS was combined with FMEA to analyze port risks [106], while interval type-2 fuzzy sets were integrated with FMEA to conduct oil spill risk assessments [38].

By combining BN with other methods, a more comprehensive analysis method can be adopted, such as BN-FMEA [95], BN-FTA [97], and BN machine learning [98]. The use of BN in risk assessments has made significant advancements; scholars have begun to explore the integration of time-sliced temporal data into BN models, known as DBN [12], which is used to model the evolution of a system over time. For instance, Jiang and Lu [44] presented a DBN model for assessing the dynamic risk of maritime accidents.

In recent years, scholars have attempted to combine CN with other methods to study the maritime transportation network from the perspective of resilience. Yang and Liu [90] constructed the Maritime Silk Road shipping network using the CN method and then used disruption simulations to analyze the resilience of the Maritime Silk Road transportation network, identifying dominant and weak port nodes. Wan et al. [49] used the resilience loss triangle model to analyze the performance of liner shipping networks (LSNs) during recovery, and the rationality and feasibility of the developed indicators in LSN-aided decision making were tested from the recovery strategies based on the degree of centrality, closeness of the degree of centrality, and betweenness centrality. Poo and Yang [107] assessed the global shipping network focusing on climate resilience by using a methodology that combined CN and a ship routing optimization model.

Simulation methods were used to study the operation of real-world or theoretical processes or systems in various pre-defined environments for different purposes (e.g., numerical testing and exploring new states) [108]. Simulations provide a more comprehensive understanding and accurate prediction of the impacts resulting from different game strategies. Game theory and simulation have been combined to discuss the impact of investment behavior on maritime transportation. In order to provide insights into resilience improvements for maritime transportation, Chen et al. [104] used the network game theory to investigate the impact of participants' investment decisions on maritime logistics network resilience and simulated participants' investment strategies in the face of catastrophic accidental explosions, labor strikes, and terrorist attacks. Liu et al. [109] applied the game theory model to study the pre-disaster investment strategies of two neighboring seaports and conducted a numerical simulation to evaluate the stability of a co-operation mechanism.

This study revealed that a new trend in recent years is the use of combined methods and coupled analysis. The application of combined methods and coupled analysis can enhance maritime transportation safety and management; furthermore, BN, fuzzy logic, CN, and simulation are generally combined with various methods.

6. Discussion and Future Research

6.1. Quantitative and Systematic Assessment of Maritime Transportation System Resilience

Due to the frequent occurrence of natural and man-made disasters, the concept of resilience is gradually emerging. Resilience was first proposed by Holling in the field of ecosystem research [110]; then, it began being widely used in other fields, including economics [111], psychology [112], and system engineering [113]. The core concept of resilience is the ability of a system to resist and recover performance from unexpected disruption events. The hypothetical system performance of the curves under normal conditions and in the face of destructive events can be referred to [108], which attempts to incorporate as many resilience features as possible. For maritime transport systems, it is critical to mix methods and tools to compare the results of maritime resilience under disruptive events. To date, some studies have assessed maritime resilience from the network topology viewpoint [90], but few have included performance indicators via quantitative evaluation. In the future, the metrics used to evaluate maritime resilience are worthy of our consideration. Furthermore, it is necessary to develop new indicator assessment frameworks and incorporate the features of maritime resilience. Although the TOSE (technical, organizational, social, and economic)–R4 (robustness, redundancy, resourcefulness, and rapidity) framework for assessing community earthquake resilience has been studied for many years, relevant research framework on maritime resilience is still in its infancy. The TOSE–4R framework provides a reference for maritime resilience analysis. More importantly, how to analyze the dynamic interaction process between maritime resilience and external perturbations based on actual scenarios is worth studying. However, it should be noted that the Russia–Ukraine war has greatly disturbed the shipping market; thus, a potential research direction is to discuss maritime resilience in the context of the Russia–Ukraine war on the future research agenda.

6.2. Data- or Intelligence-Driven Technologies for Maritime Safety and Emergency Management

In terms of maritime safety modeling, in the early stage, expert knowledge remains an essential data source when essential data are unavailable or incomplete from relevant investigations; however, expert knowledge is argued to be subjective and uncertain [114]. The data-driven approach as an emerging method that reduces the subjectivity of research and is more consistent with the actual situation; nevertheless, in the face of diverse data types and extensive data sources, obtaining and extracting effective information is a challenge. Industry 4.0, which is the deep integration of information and intelligence, can be considered the current trend of data exchange in manufacturing processes and automation. Industry 4.0. After Industry 4.0, intelligent technology has penetrated into various industries, including maritime transportation areas, and the Internet of Things, big data analysis, artificial intelligence, and cloud computing are the key focus directions. Intelligent technology is used to process massive data, extract valuable information, and enhance the intelligent capacity of maritime transportation safety and emergency management. With the aid of advanced intelligent technology and concepts, combining intelligent data and historical data with machine learning and other model algorithms to realize intelligent safety and emergency management is worth exploring. First, knowledge related to safety and emergency management, including event information, warning rules, and processing procedures, can be represented. Second, the semantics related to safety and emergency management can be parsed and reasoned to identify the risks and hidden dangers. Finally, an intelligent monitoring, assessment, and early warning system can be established to realize the real-time monitoring and early warning of maritime transport safety and emergency management.

6.3. Scenario Representation and Digital Twins Are Becoming Critical and Practical for Maritime Emergency Research

Maritime emergencies occur frequently, causing great damage to the environment and society. When a maritime emergency occurs, an immediate response is important for minimizing the damage. There needs to be a balance between the focus on preventative safety efforts and the extent of emergency preparedness provisions. Currently, existing research focuses on the location of the emergency supplies reserve base, rescue resource allocation, and configuration optimization of salvage vessels [91,115]. Moreover, most research has taken oil spills as a case to analyze emergency resource dispatching [92,116]. Notably, in the future, comparative analyses of the application effects under different emergency scenario levels will be important for improving the efficiency of maritime emergency salvage. Moreover, climate change and the development of sea routes have increased maritime activity in the Arctic, which increases risks of maritime accidents, such as oil spills, collisions, and explosions. To cope with the complexity and uncertainty of Arctic maritime emergency operations caused by humans or nature in the Arctic, future studies can extend the digital twin technology into maritime emergency management, which can reduce uncertainties in the emergency operation process and optimize the integration of maritime emergency management. To achieve this objective, actual data are mapped to a digital twin; after connecting with the digital twin, the response entities from different stages dynamically adjust based on changes in the unexpected events, thereby continuously optimizing the effectiveness of maritime emergency response effects.

6.4. Issues Associated with Intelligent Maritime Shipping Require Urgent Attention for a Sustainable Maritime Industry

Despite continually improving safety records, shipping is considered a dangerous industry with a high rate of fatal injuries and high consequences of maritime disasters, with investigations of the underlying causes of marine accidents tending to point to human error as the single greatest contributor, estimated to be involved in 75–96% of all accidents [117]. Furthermore, due to the high impact of human errors, autonomous ship development has become an important issue in the shipping industry. At present, multiple studies are focusing on the risk identification of autonomous ships. For example, Wróbel et al. proposed a model for the safety assessment of autonomous merchant ships [118], Fan et al. identified the factors influencing navigational risk for autonomous ships [119], and a framework for risk modeling was outlined for autonomous ships by Utne et al. [120]. However, thus far, few research works have quantified the risk management techniques for autonomous ships, and the percentage of accidents that can be prevented by risk management techniques has not been quantified. In this context, safety management frameworks are the direction of autonomous ships moving forward. To achieve autonomous ships that are safe at sea, the first step is to establish a mapping relationship between safety management framework functions and risk evolution characteristics. Embedding a multi-agent model for human–autonomous ship interaction follows this, with a subsequent consequence assessment of the application of safety management technology, which is crucial based on autonomous shipping scenarios.

7. Conclusions

An updated literature review can identify the hotspots and trends of a thematic discussion. In this study, we used systematic and bibliometric reviews to examine 186 articles published on maritime transportation safety management between 2011 and 2022, which allowed to provide a comprehensive summary and mapping of this topic. The results show that most authors examined maritime safety and emergency management from risk assessment, emergency resource optimization, vulnerability analysis, and resilience measurement perspectives. This study also provided a specific elaboration on the main research methods. Maritime transportation safety management assessment methods have undergone a qualitative analysis and quantitative evaluation. Most journals contribute articles using BN, fuzzy theory, and simulation methods. Recently, studies have focused on mixed methods and advanced tools (e.g., deep learning and dynamic programming models) to analyze maritime safety and emergency management issues. Analyzing maritime safety management publications can be helpful, especially in assisting researchers in effectively finding suitable directions for upcoming research. This study provides an initial, comprehensive, and systematic evaluation of the literature on maritime safety management. The findings serve as the foundation for further investigation of maritime safety management concerns. This review article provides guidance for essential future research topics, such as maritime resilience, data-driven analysis, emergency evacuation, and autonomous ship navigation safety development.

However, there are some limitations to our research. First, the bibliometric approach can only provide a high-level overview of the maritime transportation safety and emergency management field. Therefore, a systematic literature review is recommended to gain more detailed insights. Second, using other databases, such as the Springer or Scopus database, may produce different results. Third, the high citation rate indicates that these articles have made significant contributions to the development of maritime transportation safety management; however, high citation rates do not mean correctness of the academic research results. Focusing on highly cited articles may lead to the neglect of important emerging research topics.

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