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The prediction of ship groundings: A review

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ABSTRACT

Ship grounding is one of the most common and devastating maritime accidents. This article aims to present a retrospective review of models used to estimate the frequency of such incidents. Given the increasing growth of maritime traffic, this is the type of maritime accident that today's modern science should better address and present modern solutions to minimize such accidents. Numerous grounding risk assessment models have been developed throughout the history of maritime research, contributing significantly to the reduction of ship grounding incidents. However, while research and related models on this topic are abundant, they are often unstructured and fragmented, lacking detailed and comprehensive analysis necessary to clearly identify key shortcomings and areas for improvement. A thorough search of relevant databases was conducted to better capture academic articles and general publications addressing the estimation of ship grounding frequency. Using the bibliographic mapping capabilities of the VOSviewer software, the study identified research clusters related to grounding issues. The inclusion of bibliometric analysis enhances this article by providing a comprehensive overview of the literature and highlighting the researchers who have made the most significant contributions to the development of ship grounding assessment models—thus laying the groundwork for future advancements.

1 Introduction

Grounding is a type of maritime accident that can cause damage to a ship, and in some cases, the loss of the vessel, potentially resulting in the loss of human life. It is also an accident that can lead to marine pollution through the leakage of fuel or cargo from the ship. Navigational accidents caused by ship groundings account for about one-third of commercial ship accidents [1]. Considering that maritime traffic is increasing each year, this type of accident should not be underestimated; it can be extremely dangerous and, in certain situations, even fatal.

For these reasons, it is crucial to assess the grounding risk or to determine the frequency of ship groundings in a given area. Looking back through history, both the maritime industry and the International Maritime Organization (IMO) have made significant efforts to improve maritime safety. However, the number of maritime accidents remains considerable to this day [2]. When it comes to ship grounding risk, researchers have continuously sought to address this issue through various methodologies, aiming to identify the factors that contribute most to ship groundings. Although, in the end, different risk assessment methods may yield varying results [3].

The literature discussed in this paper primarily focuses on the field of ship grounding frequency research. However, conducting a bibliometric review of this literature not only helps understand the overall trend in ship grounding research but also provides new insights and lays the foundation for future improvements in this area.

2 Research Methodology

This chapter focuses on the methodological approach that aims to provide an empirically structured foundation for the further development of new ship grounding frequency models. To ensure an appropriate standard for the entire review process, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed in this paper [4]. The reason for using the PRISMA method is its widespread adoption as a systematic approach that is easy to follow. The flow of information based on the PRISMA method is shown in Figure 1, and the steps are explained below. The VOS Viewer software was used for data analysis.

One of the main motivations for reviewing various scientific papers on ship grounding lies in the ambiguity surrounding the definition of different model categories, as well as the classification of individual models into different subcategories. Therefore, this research, in reviewing the existing scientific literature on the topic of ship grounding, aims to address the categories of grounding models, model characteristics, the factors considered when developing these models, and the chronological history of research on grounding frequency. This paper will also present the advantages and disadvantages of existing models, propose potential improvements, and offer its own considerations.

2.1 Identification of Research Papers

A systematic literature review (SLR) method was used to explore the available scientific literature on this topic. This review was conducted in a top-down approach, focused on a narrowly defined research question: the frequency of ship groundings. During the process, all evidence from the literature that answers the question was identified, evaluated, selected, and compiled. The steps preceding the compilation of the systematic review article consisted mainly of defining the problem, searching for scientific literature (i.e., articles that reliably address the grounding issue), sorting the scientific articles to select those relevant to the defined topic, evaluating the quality of the selected articles, and finally, combining and sorting them before reaching the conclusion. The main goal of this chapter is to identify scientific papers, articles, and studies that address the specified topic, analyze them, and, at the end of the chapter, provide a summary conclusion based on all the scientific papers included in the systematic review.

3 Bibliometric Analysis

3.1 Database Search Results and Filtering Process

In order to obtain a systematic review of the papers, the exclusion criteria applied to the search were:

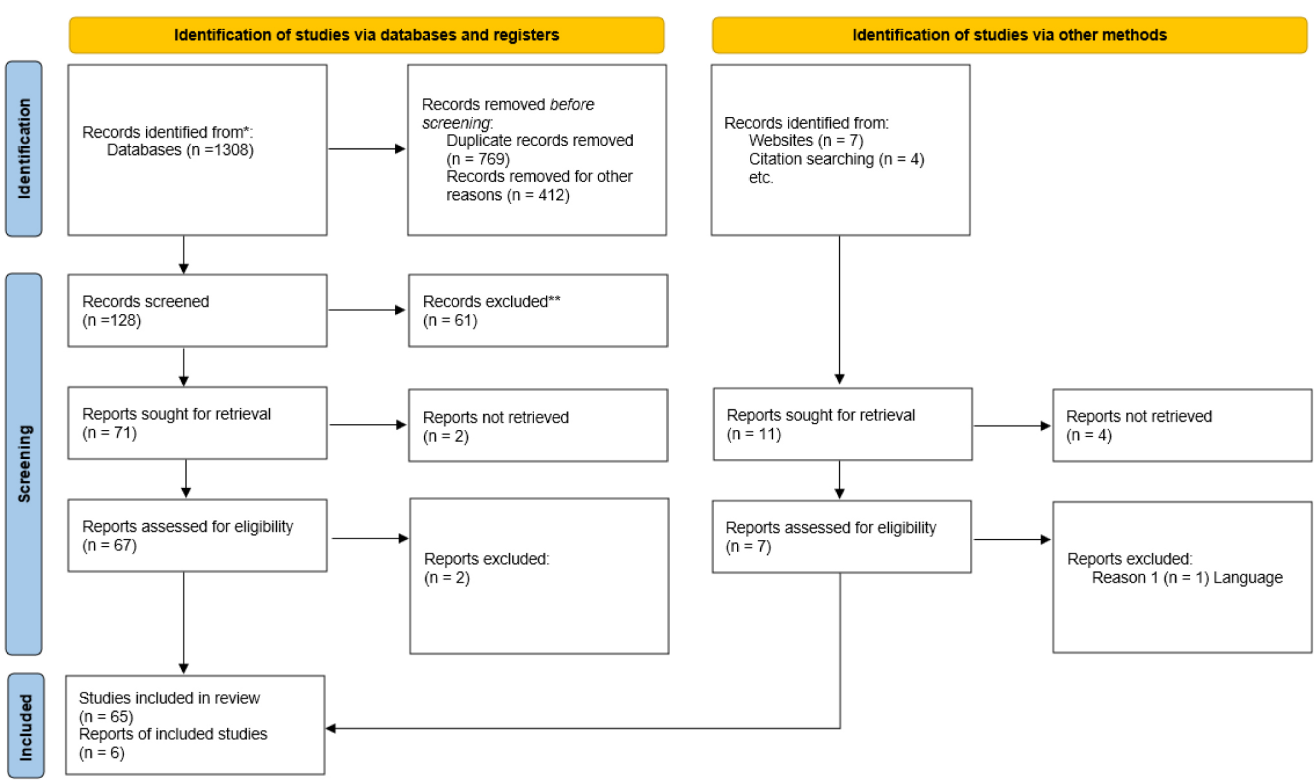

Figure 1 PRISMA 2020 analysis flow diagram for new systematic reviews, including database and other source searches [5]*. Records identified were from the Web of Science Core Collection, Scopus, and Google Scholar databases. All literature exclusions were made by the author of this paper.

abstracts, presentations, extended abstracts, and review articles. The following relevant databases were searched:

- Web of Science (WoS)
- Scopus
- Google Scholar

The WoS and Scopus databases provide rigorously peer-reviewed research, as they are known for indexing high-quality peer-reviewed journals, conference proceedings, and other scientific publications. Google Scholar was used to complement the bibliographic databases by including a wider range of sources. During the search, keywords were selected based on the most commonly accepted terms and phrases from the literature. Additionally, various combinations of keywords were used as search input, followed by manual searches to identify papers based on titles, abstracts, and introductions. The keywords and their combinations used in the database searches were:

- Ship grounding
- Grounding frequency
- Grounding possibility
- Grounding estimation

The selection of primary keywords in this study was based on the research objectives, with the aim of analyzing and identifying relevant literature on the topics of "ship grounding" and "grounding frequency." These keywords formed the basis for the search strategy. However, the search was supplemented with related terms, such as "grounding possibility" and "grounding estimation," to encompass a broader network of relevant literature that the primary keywords alone could not cover. To ensure the reliability of the research data, the Web of Science (WoS) was used as the primary source for literature searches, as it is considered the most comprehensive literature database in the world [6]. The time period for the search was not restricted, and the language of the literature search was set to "English."

In WoS, 3,300 papers were found under the keyword "ship grounding." By applying the search filter, 1,308 documents were identified, and a query link for this search is provided here: https://bit.ly/45aQfXV. Under the keyword "grounding frequency," with the search filter settings, 1,011 documents were found, and the query link for this search is: https://bit.ly/4dhzL2i. For the keyword "grounding possibility," with the search filter settings, 251 documents were found, and a query link is provided here: https://bit.ly/43jkWI6.

Subsequently, irrelevant documents were removed through manual review based on the found papers. For example, in some papers, ship groundings are discussed in segments such as: frequency of groundings, environmental pollution caused by ship groundings, deformation of ship structures caused by groundings, factors causing groundings, research on maritime grounding accidents, and risks associated with groundings. Only those papers closely related to the research topic were selected.

In Scopus, using the search filter for the keyword "ship grounding," 563 articles were found, with the query link here: https://tinyurl.com/yvt22pc7. For the keyword "grounding frequency," 229 articles were found, with the query link: https://tinyurl.com/5yx3awj3. For the keyword "grounding possibility," 25 articles were found, and the query link is: https://tinyurl.com/3r8wese7.

Google Scholar provided a large number of sources for the aforementioned keywords. However, at this stage, it was primarily used to find older literature and publications related to grounding frequency. Additionally, articles not found in the WoS database were identified in Scopus (see Table 1). No duplicate articles between the WoS and Scopus databases are listed in Table 1.

Table 1 Chronological overview of the 71 highlighted papers that contributed the most to the development of ship grounding assessment models [7-77]

Literature	WoS	Scopus	Google Schoolar	Other
Y. Fuji (1974) [7]			■	
T. Mcduff (1974) [8]			■	
P.T. Pedersen (1995) [9]			■	
M.D. Amrozowicz (1997) [10]			■	
B.C. Simonsen (1997) [11]			■	
H.L. Kite-Powell (1999) [12]		■		
T.G. Fowler (2000) [13]	■			
S. Otto et al. (2002) [14]	■			
P. Friis-Hansen (2002) [15]	■			
L. Zhu (2002) [16]	■			
M.J. Briggs (2003) [17]	■			
S. Kristiansen (2004) [18]				■
Rambøll (2006) [19]				■
L. Gucma (2006) [20]	■			
N.M. Quy (2007) [21]			■	
M.S. Eide et al. (2007) [22]	■			
L. Gucma (2007) [23]		■		
COWI (2008) [24]				■
Ö.S. Ulusçu et al. (2009) [25]	■			
J. Yitalo (2010) [26]			■	
J. Montewka et al. (2011) [27]	■			
F. Kaneko (2012) [28]	■			
A. Mazaheri (2013) [29]	■			
D. Zhang et al. (2013) [30]	■			

Literature	**WoS**	**Scopus**	**Google Schoolar**	**Other**
Z. Lušić, S. Kos (2013) [31]	■			
A. Mazaheri (2014) [32]	■			
Y.L. Ren (2014) [33]				■
A. Mazaheri et al. (2015) [34]	■			
M.E. Khaled, Y. Kawamura (2015) [35]	■			
Y.E. Senol (2016) [36]	■			
M. Przywarty (2016) [37]	■			
M. Karlsson et al. (2017) [38]			■	
M.E. Khaled, et al. (2018) [39]			■	
M.M. Abaei et al. (2018) [40]	■			
A. Baksh et al. (2018) [41]	■			
J.C. Huang et al. (2019) [42]	■			
B. Wu et al. (2020) [43]	■			
H. Karahalios (2020) [44]	■			
A. Bakdi et al. (2020) [45]	■			
Y. Tang et al. (2020) [46]		■		
S. Fan et al. (2020) [47]	■			
M. Jiang et al. (2020) [48]	■			
A. Hörteborn (2021) [49]	■			
S.T. Ung (2021) [50]	■			
B. Sahin et al. (2021) [51]	■			
C. Sakar et al. (2021) [52]	■			
L. Vojkovic et al. (2021) [53]	■			
D. Jiang et al. (2021) [54]	■			
K. Liu et al. (2021) [55]	■			
C. Zhao et al. (2021) [56]	■			
S. Fu et al. (2022) [57]	■			
M. Zhang et al. (2022) [58]	■			
X. Ma et al. (2022) [59]	■			
C. Fan et al. (2022) [60]	■			
D. Öztürk, K. Sarıöz (2022) [61]	■			
W.S. Kang et al. (2022) [62]	■			
T.T. Enevoldsen et al. (2022)[63]	■			
M. Zhang et al. (2023) [64]	■			
L. Yang et al. (2023) [65]	■			
S. Liao et al. (2023) [66]	■			
A.L. Tunçel et al. (2023) [67]		■		
J.C. Carmona et al. (2023) [68]			■	
R.G. Maidana et al. (2023) [69]	■			
D. Yazir et al. (2024) [70]	■			
L. Ma et al. (2024) [71]	■			
C. Fan et al. (2024) [72]	■			
M. Kaptan, O. Bayazit (2024) [73]	■			
Y. Yu et al. (2024) [74]	■			
L. Ma et al. (2024) [75]	■			
Z. Munim et al. (2024) [76]	■			
C. Fan C et al. (2024) [77]	■			

Therefore, the term “grounding” was chosen as the main research topic to ensure correlation with ship grounding.

The graphical search analyses in Figure 2 demonstrate the value of tools for identifying effective keyword choices, such as “ship grounding.” A visual overview of the detailed keyword exploration using semantic links is provided by VOS Viewer. This program displays an analysis of authors, countries, and inter-institutional collaboration networks, thereby helping to assess the current state of research collaboration in the field of ship grounding research [78]. This approach enhances the understanding of research topics and helps identify potential areas of convergence or divergence within a comprehensive research framework.

The visual analysis of the papers is displayed using the VOSviewer software. Afterward, the results of the visualization are analyzed, and relevant conclusions are drawn about the specific research topic, such as ship grounding in this case. The VOSviewer program divides the ranges of the research topic by color on the knowledge map (Figure 2), clearly showing the strength of the connection between ship grounding and other keywords, thereby improving the understanding of the research topic. The strongest link strength is found for the keyword “ship grounding” with a value of 338.

This bibliographic merging approach in the VOSviewer software revealed research clusters related to the issue of ship grounding, which include several subcategories, such as: frequency of grounding, environmental pollution caused by ship grounding, deformation of ship structure caused by grounding, factors causing grounding, research on maritime grounding accidents, grounding risk, etc. The size of the nodes in Figure 3 indicates the number of papers related to ship grounding published in the corresponding journal, while the thickness of the connecting lines indicates the closeness of the links between the journals. The color of the nodes and lines represents the similarity of the journal topics. From this, it can be seen that there is a connection between various scientific journals within the similarity of the topics of the published papers. According to a search for the keyword “ship grounding” within the WoS database, the journals with the strongest link strength are: Ocean Engineering, Journal of Marine Science, Marine Structures, etc. (Figure 3).

A visual network of international collaboration in the field of ship grounding is presented in Figure 4. The size of each node represents the number of publications from a given country, while the thickness of the lines between nodes indicates the level of collaboration between countries. According to the keyword search for ‘ship grounding’ in the Web of Science (WoS) database, as shown in Table 2, China makes a significant contribution to this field with 340 publications, followed by the USA, the UK, Canada, Australia, South Korea, Norway, and several other countries.

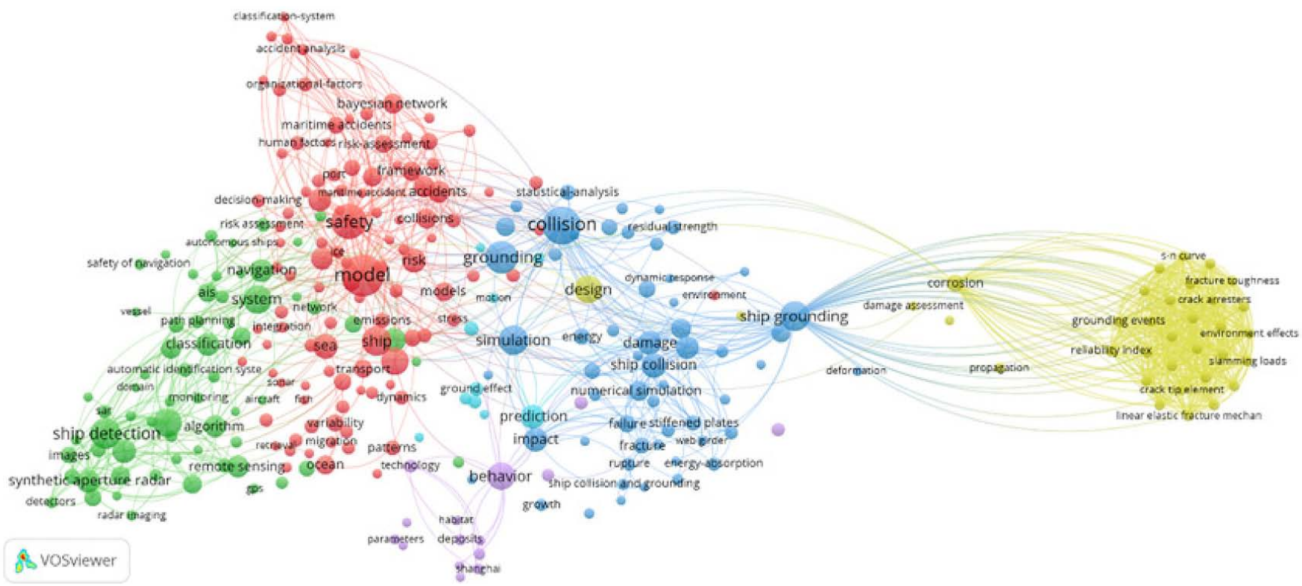

Figure 2 Link between the keyword "ship grounding" and the 44 most frequently used keywords in the research (VOS Viewer). Cluster 3, links: 107, occurrences: 44

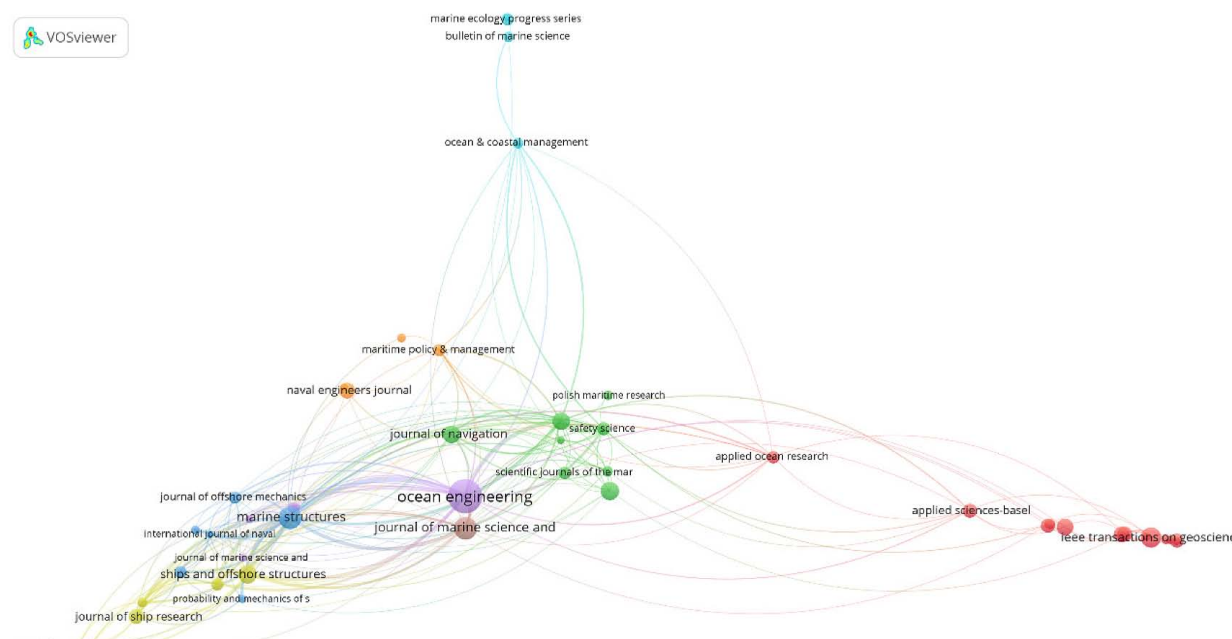

Figure 3 Type of analysis – citation; sources with the highest total link strength presented in the VOSviewer software

Table 2 The top seven countries by number of scientific publications retrieved from the Web of Science (WoS) database using the keyword 'ship grounding'

Country	Documents	Citations	Total link strength
China	340	6509	83
UK	90	3868	65
USA	193	6953	50
Canada	44	1493	32
Australia	53	1993	31
South Korea	91	1435	27
Norway	74	2339	24

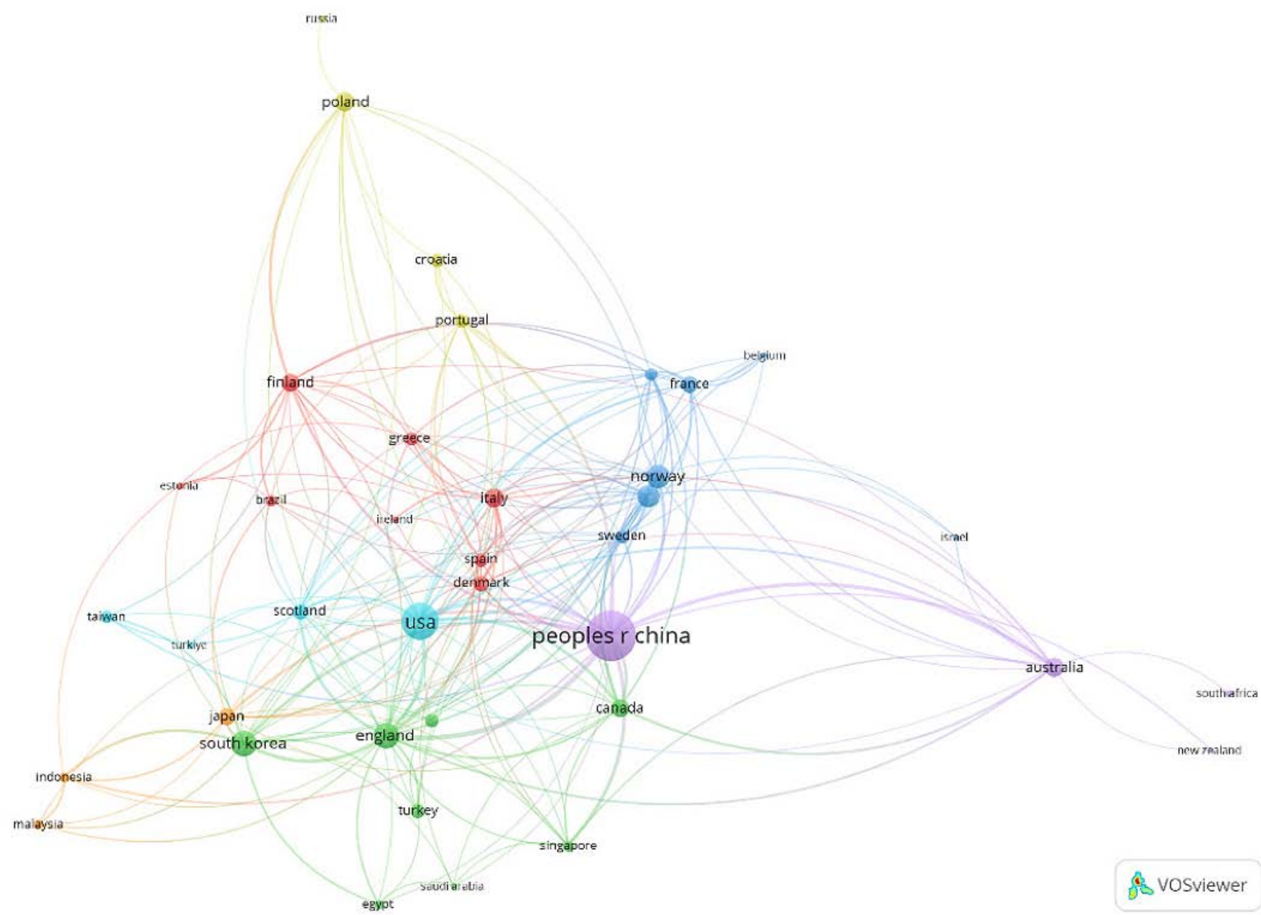

Figure 4 National collaboration network in the field of ship grounding, based on the keyword search 'ship grounding' in the Web of Science database

3.2 Overview of Research Papers

The second phase involved the development of a strategy to extract and identify research papers addressing the frequency of ship grounding through various approaches. This step reduced the number of publications for analysis and enabled a more in-depth review of the most relevant studies. During this phase, the titles and abstracts of the papers were examined, and, where necessary, the full texts were also reviewed. Publications that were not written in English or that were not directly related to ship grounding, its frequency, or its probability were excluded. In addition, duplicate entries were identified and removed. A manual screening of the 127 retrieved papers was then conducted to eliminate irrelevant documents. For instance, some papers referenced ship grounding in the context of topics such as grounding frequency, environmental pollution resulting from grounding, structural deformation due to grounding, causative factors, marine accident investigations, and grounding risk assessments. After excluding irrelevant publications, a total of 71 papers directly addressing the frequency of ship grounding were selected. The annual distribution of these publications is presented in Figure 5.

Based on Figure 5, it can be concluded that the number of papers related to the development of ship grounding frequency models has been steadily increasing since 2016, with a significant peak observed between 2020 and 2024. This trend suggests that research in the field of grounding probability has been receiving growing attention in recent years. Furthermore, it is likely that this upward trajectory will persist, reflecting a sustained interest and progress in the area of ship grounding research.

3.3 Evaluating the Acceptability of Research Studies

The third phase of the search involved selecting articles that were specifically focused on the development of models for estimating the frequency of grounding. During this phase, papers relevant to the research topic, which includes reviewing the published literature on ship grounding and grounding frequency, were selected. In this step of the analysis, the relevant literature was

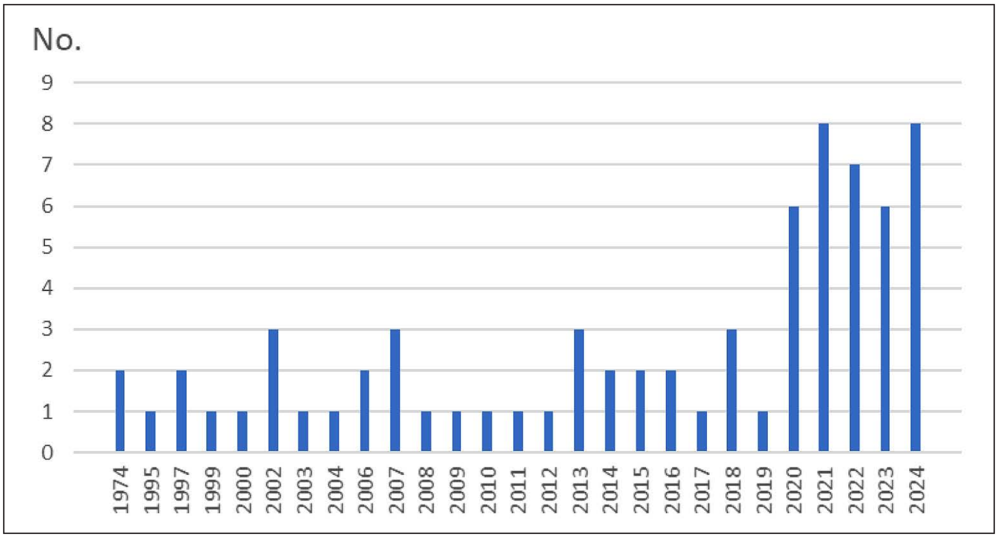

Figure 5 Overview of selected literature on the frequency of ship grounding: publication statistics for the period 1974 to 2024

thoroughly reviewed, and its relationship to the research questions was established. Literature that was not closely related to the topic of ship grounding or the frequency of grounding was excluded from further consideration. The literature search was completed on January 1, 2025. During the selection process, the broadest possible scope was considered in order to ensure comprehensive coverage of the topic and to address the research questions effectively. After the review, 71 scientific papers were deemed relevant. This set of papers includes literature that contributed to the development of grounding frequency models and is discussed in this paper.

3.4 Analysis of Selected Research Studies

This section presents a review of key scientific papers on the topic of ship grounding, organized chronologically. The goal is to identify the foundational models upon which later research is based, highlight the leading countries in this field, and determine the main authors contributing to grounding frequency models, based on a bibliometric analysis of scientific publications.

4 Critical Analysis and Review of the Considered Models Regarding Grounding Frequency

Groundings typically occur due to navigational errors while the ship is underway under its own power, and this type of grounding is the most common [79]. These incidents often result from errors in voyage planning [10]. A second, less frequent type of grounding occurs when the ship runs aground near the shore due to external factors such as wind, currents, or waves [79].

Overall, models addressing grounding frequency or probability can be examined chronologically, starting from the earliest examples. This approach allows for an analysis of how different authors developed their grounding models in an attempt to represent real-world events as accurately as possible, thereby contributing to greater safety in maritime traffic.

Models can also be divided into analytical models, which do not use the distribution of ships in their structure, and statistical models, which do. Furthermore, models can be categorized according to internal and external factors—those that directly cause groundings and those that are considered during the development of grounding frequency models.

The development of grounding frequency models began with Fuji (1974), whose model estimates the number of groundings, and McDuff (1974), whose model calculates the probability of such events [7,8]. Pedersen (1995) introduced a model that categorizes different types of groundings and estimates their frequency [9]. Notably, Pedersen incorporated a time factor, enabling the model to estimate the expected number of groundings on an annual basis.

A simplified version of the model, applicable to various grounding scenarios, was proposed by Otto (2002) [14]. Kristiansen (2004) combined elements of the Fuji and McDuff models in his own approach [18]. He first calculated the probability of a ship striking an obstacle in the waterway, and then derived the causation probability by multiplying the initial probability by a causality factor. Although Kristiansen presented his model as an alternative approach, he emphasized that the resulting probabilities should not be interpreted as precise figures for real-world scenarios.

The model developed by Rambøll Danmark (2006) provides an estimate of grounding rates, similar to Pedersen's model [19]. It defines two main scenarios: in the first, a ship is sailing toward an obstacle and, if no evasive action is taken, becomes a candidate for grounding. In the second scenario, a ship is navigating a bend in a channel and, if it fails to alter its course before the turning point, it is likewise considered a grounding candidate.

Simonsen (1997) refined Pedersen's model and defined the expected number of grounding events using his modified version [11]. The models proposed by Pedersen and Simonsen serve as the foundation for computer-based grounding simulations such as COWI, IWRAP, and IWRAP Mk2 [15,24,46,62,65].

Kite-Powell et al. (1999) based their model on Bayes' theorem of probability theory [12]. Although this model does not identify specific grounding candidates, it is valuable for determining causality. Briggs et al. (2003) developed a numerical model for designing a port approach channel that takes into account navigational conditions for a specified ship. The model consists of four components: a Poisson probability distribution for the number of ship arrivals, a Bernoulli distribution for the grounding probability of a single random ship arrival, an estimation of the Bernoulli parameter based on model tests, and the calculation of recurrence intervals or return periods. The authors argue that this approach offers a more accurate estimate of vessel accident probabilities than standard port design guidelines [17]. Montewaka (2011) introduced a model for analyzing the risk of two types of maritime accidents: collisions and groundings. The model applies a risk calculation formula that considers both the probability of an undesired event and its consequences. It can be represented in a block diagram, with interconnected modules for collision probability, grounding probability, and accident consequences. The probability of vessel collision is estimated using a model based on the minimum distance to the point of accident [27]. Kaneko (2012) incorporated grounding frequency estimation into his model using ship routes and the geometry of the seabed in the study area. The model shows that the risk of ship grounding increases with deviation from the planned route, while maintaining the intended course reduces the probability of grounding [28].

Mazaheri et al. (2013) established a statistical relationship between grounding frequency, waterway complexity, and traffic distribution. The authors conducted a statistical analysis of historical grounding accident data for a specific area between 1989 and 2010, along with AIS data from 2010, to examine potential correlations between ship traffic and grounding incidents [29]. They analyzed the statistical relationships between traffic density and distribution, the number and frequency of groundings, and the connection between waterway complexity and actual accidents [34]. According to the authors, the findings in both papers are valid only for the studied area and cannot be generalized without further research. Lušić and Kos (2013) proposed an analytical model based on the Pedersen model, using calculated course deviation coefficients to provide an approximate estimate of groundings along route segments in coastal areas [31]. Przywarty (2016) applied a method for the quantitative assessment of selected factors influencing the grounding probability in a given area. By using grounding probability coefficients derived from statistical data, the model enables evaluation of the impact of internal and external factors on grounding frequency [37]. Karlsson's (2017) model is based on ship traffic data, tunnel and bridge geometry, navigational considerations, and statistical error rate information. Rambøll developed the computer program SHIPCOF, which simulates the behavior of potential grounding or collision candidates and estimates the number of groundings on an annual basis [38].

Zhang (2022) presents a big data analytical method for assessing grounding risk in real-world maritime environments. The method utilizes AIS data and seabed depth data from the General Bathymetric Chart of the Oceans (GEBCO). Based on this, an Avoidance Behaviour-Based Grounding Detection Model (ABGD-M) is introduced to identify potential grounding scenarios, and the probable grounding risk is quantified at observation points along ship routes during different voyages. The results indicate that the estimated grounding risk can vary significantly depending on the voyage routes, observation points, and operational conditions [58].

Fault Tree Analysis (FTA) is a systematic method for identifying the possible causes of system failure. This method is used to graphically represent different failure pathways in the form of a diagram. FTA is applied in the assessment of ship grounding risk; however, as the systems under consideration become more complex, the application of FTA becomes increasingly time-consuming and challenging. Event Tree Analysis (ETA) is a complementary method to FTA, focusing on the potential outcomes or consequences of specific initiating events identified in the fault tree. Researchers use fault trees to identify and rank the main factors contributing to ship groundings [10,11,13,16,22,26,36,52,56]. Fault trees are employed for both qualitative and quantitative evaluation of grounding probability and for prioritizing the contributing factors. Recent papers using this method are listed below.

In their paper, Eide et al. (2007) presented a model identical to the one used by Fowler and Sørgård [13], but with the inclusion of meteorological and ship dynamic data [22]. Zhu et al. (2002), based on Amrozowicz's study, use Fuzzy Fault Tree Analysis (FFTA) [16]. Karahalios (2020) applies the fuzzy analytic hierarchy process (FAHP) method to assess grounding risk in the Parana River. The authors conclude that FAHP appears useful for calculating weighting factors in river grounding incidents and suggest that the proposed tool could be applied to analyses of other areas [44]. The study by Sahin B. et al. (2021) deals with ontology-based fault tree analysis (FFTA) algorithms in a fuzzy environment for autonomous ships. The extension of fuzzy fault tree analysis by incorporating ontology-based fault tree structures allows for advanced analyses. Collision and grounding of an autonomous ship are investigated in two scenarios [51]. Zhao (2021) used FFTA and a Noisy-OR Gate Bayesian Network for navigational risk assessment in Qingzhou Port [56]. In the study by Tunçel L.A. et al. (2023), grounding risk was examined by analyzing accident reports, using FTA to obtain different accident scenarios and the method of measuring the importance of cut sets (CS-I), which were used to prioritize the scenarios. The study found that lack of communication in bridge resource management, fatigue/insomnia, and inadequate voyage planning were causes of grounding [67]. Yazir D. et al. (2024) used a hybrid method combining fault tree analysis (FTA), the full consistency method (FUCOM), and event tree analysis (ETA) to analyze causes of maritime accidents involving collisions and groundings, regardless of ship type. According to the authors, the main causes of groundings are severe weather conditions, insufficient supervision, engine failure, strong winds, and loss of power [70]. The study by Ma L. et al. (2024) aims to develop a complex network of human factors contributing to maritime accidents. First, a maritime accident scenario is defined based on reports of ship grounding accidents, and then human factors contributing to ship grounding are identified and structured using the Human Factors Analysis and Classification System (HFACS). HFACS is a causality model for maritime accidents designed to investigate causes related to human factors. The interrelationships between human factors are represented as nodes, edges, and edge weights in a network. Topological parameters, including degree, clustering coefficients, and node importance, are then measured for the complex network of human factors [75].

A Monte Carlo simulation is a probabilistic model that can incorporate elements of uncertainty or randomness in its predictions. It is used to estimate the behavior of complex systems or processes by simulating a number of possible scenarios and analyzing their outcomes to gain insight. Monte Carlo methods are often implemented through computer simulations and can provide approximate solutions to problems that are otherwise intractable or too complex for mathematical analysis. Some of the papers that have applied this method to estimate the probability or risk of ship groundings are listed below.

The model presented by Quy et al. (2007) consists of three distinct phases. The first phase is a real-time simulation that determines the probability distribution of traffic density and ship position. The second phase applies the Monte Carlo method to predict the outcomes of the ship's passage. The third phase involves an analytical model of the consequences of an accident [21]. The model presented by Gucma provides a graphical representation, defining a model where one of the key elements for assessing grounding risk is the designed width of the waterway [20]. Gucma's model employs a probabilistic method for navigation risk assessment based on real-time simulation results. It comprises three methods: real-time ship maneuvering simulation, the Monte Carlo method, and an analytical model of accident consequences [23]. Additionally, in the study by Uluscu et al., computer simulation models were used that generate and analyze various traffic flow scenarios within a reasonable time frame using the Monte Carlo method [25]. The deterministic model by Ren Y. L. et al. (2014) considers the ship's under-keel clearance (UKC) as a set of random variables influenced by ship maneuvering, wave impact, squat in shallow water, and seabed hydrographic data. The basic ship response to waves is predicted by computational fluid dynamics (CFD). Using Monte Carlo simulation, the stochastic uncertainty of the under-keel clearance is evaluated, and the probability of grounding can support channel design and the analysis of ship traffic safety in restricted waterways [33].

A paper by Huang (2019) analyzes the behavior of ships entering a port to quantitatively assess the risk of grounding at the port entrance and waterway using the Monte Carlo method [42]. The study by Hörteborn presents a methodology that uses AIS data and a ship maneuvering simulator to simulate and analyze maritime traffic, considering both collision and grounding risks. Three events were modeled and simulated in the simulator, and the Monte Carlo method was used to perform a large number of simulation runs. This study demonstrates how the probability of collisions and groundings can be reduced by lowering ship speed or modifying the separated traffic scheme [49].

The paper by Carmona C. J. et al. (2023) addresses the risk of grounding in inland ports. The aim was to develop a tool that leverages tidal waves through smart planning to ensure sufficient under-keel clearance at all times. AIS data and tide data along the entire waterway, obtained from measuring sensors and a calibrated numerical prediction model, were used. The grounding risk assessment was developed using the Monte Carlo method. This study considers the propagation of tidal waves, weather conditions, ship speed, and squat along the route to define the failure function, i.e., grounding. The probability of grounding is assessed by accounting for the probability distribution of all involved variables, allowing simulation of numerous random navigation events [68]. A paper by Yu et al. (2024) analyzes ship grounding accidents in Arctic waters. The authors propose a framework for maritime accident risk process analysis based on resilience theory using the Function Resonance Analysis Method (FRAM). Marine casualty groundings are identified based on investigation reports, followed by analysis of the potential variability of all relevant functions. The FRAM model is then constructed by aggregating functional variations. Using Monte Carlo simulation, coupling values of all interconnected functions are calculated [74].

Bayesian networks (also known as belief networks or decision networks) are a type of probabilistic graphical model used to build models from data and/or expert opinions. The graphical model represents a set of variables and their conditional dependencies through a directed acyclic graph. Bayesian networks are frequently applied in ship grounding research [30,32,39-41,43, 47,48,50,52-54,56,57]. They can be used to define the probabilities of different system states (such as ship location, distribution of ship types, probability of human error, etc.) at various interconnected nodes. Overall, in the field of ship grounding research, Bayesian networks and Naive Bayes are among the most commonly used methods. Given the large number of papers employing Bayesian networks, a brief overview of recent studies follows below.

In their paper, Liao et al. (2023) employed Bayesian Networks (BN) to predict the most probable causes of various types of maritime accidents. The nodes within the BN represent different contributing factors to accident causation. The factors considered include the type of accident, loss of life, accident severity, time period, gross tonnage, and type of ship. Utilizing Netica software, a Tree-Augmented Naïve Bayes (TAN) model was developed to assess accident risk based on available maritime accident data over a defined time period. Simulation-based validation of the model indicated that the consequences and severity of the accident are the two most significant predictors in determining the type of accident, followed by ship type, gross tonnage, time period, and season. The results also showed that collisions have the highest probability of occurrence among maritime accidents, followed by groundings and then fires/explosions [66].

Maidana et al. (2023) propose a method for collision and grounding risk-based trajectory planning for an autonomous ship. The method consists of two main steps. In the first step, the dynamic probabilistic risk assessment (KPRA) method is used in combination with risk models and dynamic system simulation, which together produce a ranked list of trajectories based on the risk of collision and grounding. In the second step, a risk assessment is conducted on the ranked scenarios, followed by a comparison with predefined risk acceptance criteria to determine which scenarios meet acceptable risk levels. This paper presents two primary scientific contributions. First, a Bayesian Network risk model for estimating the probability of navigational accidents is developed and integrated to enhance the KPRA. Second, a modified guidance, navigation, and control (GNC) framework for autonomous ships is proposed to incorporate risk-based planning [69].

Ma et al. (2024) developed a Bayesian Network (BN) model for a specific area based on three years of accident data. The model aims to capture individual and joint factors that most significantly influence maritime accidents, including ship groundings. This BN model was constructed using the Tree-Augmented Network (TAN) learning algorithm and the Expectation-Maximization (EM) algorithm. A comprehensive BN analysis was then conducted based on the developed TAN-BN model [71].

In a study by Kaptan and Bayazit (2024), the risk of collision and grounding accidents in port areas was assessed. The proposed model clarifies the relationship between Risk-Identifying Factors (RIFs), derived from the analysis of accident reports for a specific port area, and accident severity. The data from these reports were analyzed using the Tree-Augmented Naïve Bayes algorithm, a data-driven approach within the Bayesian Network methodology [73].

Machine Learning (ML) regression models have been widely applied in accident prediction, management, and assessment across various industry sectors, including maritime transport. However, in the maritime domain, the application of Automated Machine Learning (AutoML) for marine accident analysis remains extremely limited. Chronologically, the existing literature includes a diverse range of methodologies for analyzing maritime accidents, encompassing ML models as well as analytical techniques such as Fault Tree Analysis (FTA), Bayesian Networks (BN), and others. A key limitation is that ML models are typically trained using data specific to a particular area, meaning that accident records from other countries or regions must be re-trained before the models can be effectively deployed for accident prediction.

The study by Liu et al. (2021) is notable for developing a Bayesian Network (BN) for data analysis using an advanced Machine Learning (ML) approach, based on maritime accident data from the coastal area of China. To construct the BN, statistical interactions between causal factors derived from major maritime accident data were identified and matched. The results highlighted the importance of various risk-influencing factors and critical scenarios in coastal waters [55].

In a paper by Zhang et al. (2023), a big data analytics method is presented for the proactive mitigation of grounding risk. The proposed Machine Learning algorithm is applied to predict the movement of ships operating between two ports. The dynamics of ship motion are visualized along the ship's route using the Gaussian Process Regression (GPR) flow method. The results demonstrate that this methodology can predict the probability distribution of ship dynamics—such as speed, roll distance, drift angle, and surge acceleration—as well as grounding risk along selected ship routes [64].

In the study by Munim et al. (2024), Machine Learning (ML) was used to analyze historical accident data, including ship groundings. A total of 29 ML classification algorithms were trained, and the Light Gradient Boosted Trees Classifier (LightGBM) achieved the highest prediction accuracy. Based on the results, it was concluded that ships operating in narrow coastal waters and fishing vessels are significantly more vulnerable to grounding compared to other types of maritime accidents. The ML algorithm can be applied in the development of a decision support system for real-time risk assessment of maritime accidents [76].

Autonomous ships, or Maritime Autonomous Surface Ships (MASS), represent a significant innovation in the maritime industry, driving rapid technological developments that are expected to lead to their commercial deployment. These ships can be operated remotely or may function fully autonomously. Such a transformative shift in maritime operations necessitates robust regulatory frameworks to ensure the safety of life at sea, the protection of cargo, and the integrity of the ship itself. Given the operational characteristics of autonomous ships, it is essential to consider route planning, the availability of alternative routes, and the vessel's ability to navigate within dynamic environments. One of the primary research objectives in this area is to determine optimal trajectories that minimize the risk of encountering dynamic obstacles (e.g., collisions) or fixed obstacles (e.g., groundings). It is also worth highlighting several recent studies that have addressed grounding risk in the context of autonomous ships.

The study by Sahin et al. (2021) addresses ontology-based fuzzy fault tree analysis (FFTA) algorithms applied in a fuzzy logic environment for autonomous ships. The extension of fuzzy fault tree analysis through the integration of ontology-based fault tree structures enables more advanced analytical capabilities. Collision and grounding scenarios involving an autonomous ship were investigated in two case studies [51].

In the paper by Fan et al. (2022), a scientific approach is applied to determine the level of risk for a specific operational mode (OM) of a Maritime Autonomous Surface Ship (MASS). The proposed framework evaluates the risk level for a given OM based on expected failure modes (FMs) related to human factors, organizational structure, the ship, environment, and technology. These FMs and their associated accident scenarios (ASs) are identified from conventional ship accidents in a defined geographic area. The navigational risk metric for a MASS in a specific OM, estimated based on the expected ASs, uses interval-based risk priority numbers (RPNs) to reflect inherent uncertainty. By ranking these metrics using interval values across three operational modes, a comprehensive risk profile was obtained. The feasibility of the proposed risk comparison framework was evaluated using grounding scenarios in coastal waters where relevant accident data were collected [60].

In the article by Enevoldsen (2022), a Short Horizon Planner (SHP) is proposed for decision support or automated route deviations for Maritime Autonomous Surface Ships (MASS), as a means to mitigate prevailing risks such as collision or grounding. SHP is specifically designed to calculate alternative routes for collision and grounding avoidance. The proposed framework is demonstrated through several scenarios within a defined geographic area [63]. The optimal sampling-based collision and grounding avoidance problem is presented as a modified version of the approach introduced by Gammell et al. [80]. Rapidly-Exploring Random Trees (RRTs) are employed, where grounding avoidance is addressed through a specialized sampling scheme that triangulates the navigation chart.

In the study by Fan et al. (2024), a comprehensive framework is proposed for developing a risk matrix based on the fuzzy Analytic Hierarchy Process (AHP) with Interval Type-2 Fuzzy Sets (IT2FS) in the context of MASS. According to the authors, the results demonstrate that the proposed approach is feasible for this type of ship [72].

As a continuation of the work by Fan et al. (2024), a framework for analyzing operational risk associations using the N-K model for Maritime Autonomous Surface Ships (MASS) is proposed. Based on maritime grounding accidents in a specific area, a 24Model—a widely used accident analysis method in China—was developed to identify failure modes (FMs) of MASS related to interactions with the environment and ship subsystems. The 24Model has been recognized for its suitability in analyzing and statistically characterizing a wide range of accidents, particularly in the context of safety management for intelligent systems. Considering the three operational modes (OMs), the FMs are classified into five types of risk: human, organizational, ship-related, environmental, and technological. Based on this classification, the N-K model is applied to connect risks across scenarios that involve multiple risk categories. These scenarios are then ranked according to their risk association values for the three OMs, and the results are compared across the different modes of operation [77].

5 Discussion

The review of the literature indicates that ship grounding is among the most dangerous types of maritime accidents, posing serious risks to people, ships, and the environment. The primary cause of ship groundings is the human factor [10,12], followed by environmental influences such as sea currents [81], tidal variations [82], visibility [10], wind [10], waterway depth [10], waterway geometry [81,82], ship age [83], ship size [12,83], ship type [10], and speed through navigational areas [84]. Over time, researchers have attempted to quantify grounding risk through a variety of models. Among the earliest conceptual approaches were the mathematical models developed by McDuff (1974) and Fuji (1974). Later, Pedersen (1995) proposed a statistical model that classified groundings into four categories and introduced a time factor, enabling the estimation of annual grounding frequency. Simonsen (1997) further refined Pedersen's model, resulting in a version capable of predicting the expected number of grounding events. This modified model laid the foundation for software tools such as COWI and IWRAP, which are designed to estimate grounding frequency. The IWRAP Mk2 program, in particular, includes a module that quantifies risks associated with ship traffic in a given area. These tools rely heavily on traffic distribution data, which can be extracted from AIS databases. If comprehensive AIS data are not available for a given area, the reliability of the results is significantly reduced. Moreover, such models are highly sensitive to changes in traffic patterns and often fail to account for environmental conditions.

Computer simulation technologies have also found application in grounding risk research. Instead of providing an exact mathematical result that accounts for all possible input and output parameters of a physical system, the Monte Carlo method—also known as multiple probability simulation—employs random sampling and statistical processing. This method is well suited for computer implementation, as it relies on random number generators and the processing of large datasets. The accuracy of a Monte Carlo simulation largely depends on the quality of its underlying assumptions and input parameters. Bayesian Networks (BNs) have become a widely used method for risk assessment, particularly for modeling rare accidents. This approach is especially useful when historical data are insufficient to support the application of traditional statistical methods, as it can incorporate expert knowledge. In the maritime domain, BNs are extensively applied for risk prediction by modeling the causal relationships involved in ship accidents, including human and organizational factors. In most studies, ship characteristics, environmental conditions, human errors, and organizational elements are integrated to build BN models and to populate the conditional probability tables (CPTs). While incorporating expert judgment allows for modeling in data-sparse environments, it can also introduce subjectivity and bias. In contrast, data-driven Bayesian Belief Networks are considered more objective, as they learn from empirical data and minimize human influence [85].

In recent years, Machine Learning (ML) has emerged as a cutting-edge approach in the research of ship grounding accidents. ML is a computational technique grounded in statistics, probability theory, approximation theory, and complex algorithms, and it can significantly enhance learning efficiency [86,87]. The primary goal of ML is to enable computers to autonomously acquire knowledge and skills through data-driven learning and to continuously improve their performance over time [58]. When combined with big data, ML methods have become vital tools in the analysis of maritime accidents. With the continued advancement of ML techniques and their integration with large-scale statistical datasets, the analysis of such accidents has become increasingly precise and comprehensive. However, all ML models share a fundamental requirement: access to statistical data specific to the area of interest. Only location-specific data can yield reliable estimates of causal probabilities. Therefore, obtaining the largest possible volume of high-quality data is essential for identifying the key factors that influence grounding frequency when modeling ship grounding accidents [88].

With regard to specific research areas, Arctic shipping has been expanding due to changes in the marine environment, such as the reduction in sea ice extent and the decline of older, thicker ice. These changes have significant implications, including longer sailing seasons and access to previously unreachable Arctic routes. In recent years, Arctic waters have received growing research attention in the context of grounding risk, and several studies have been published on this topic [44,71]. Another prominent research area in contemporary maritime science is Maritime Autonomous Surface Ships (MASS), which represent a promising future for maritime transport. MASS are equipped with more advanced and integrated systems compared to conventional ships. It is expected that they will comprise a range of heterogeneous elements—such as humans, software, and hardware—functioning as a complex, interdependent system [60,77,85,89]. Several studies have also addressed the grounding risks associated with MASS operations [44,71].

6 Conclusion

This paper conducted a literature review using selected keywords to identify and include scientific studies addressing the frequency of ship groundings. The VOSviewer software was used to visualize the research landscape in this field, revealing research clusters related to ship grounding that span multiple subcategories. Papers and publications focusing on grounding frequency were highlighted, followed by a bibliometric analysis of the considered models. These models range from early analytical approaches by McDuff and Fujii to modern simulation models that incorporate machine learning. Simulation models are particularly valued for their ability to represent complex, uncertain relationships in estimating grounding probability for a given area. However, in cases where sufficient data are lacking, simulation models may incorporate expert knowledge, which introduces a degree of uncertainty and bias. As more data become available, these models can be updated accordingly. For this reason, simulation models require large volumes of accurate data in order to identify the key factors influencing grounding frequency in a specific region. In recent years, the Arctic region has emerged as a prominent area of interest in maritime accident research, largely due to global climate change. The growing commercial value of Arctic shipping routes underscores the importance of risk analysis, especially given the extreme weather conditions and iceberg hazards that exist in the region. It is therefore expected that future research will continue to explore grounding risks in Arctic waters. Additionally, recent studies have examined safety-related factors in the context of Maritime Autonomous Surface Ships (MASS), which represent the future of maritime transport. While the literature confirms that the human factor remains the leading cause of ship grounding accidents, a shift is anticipated with the increasing use of remotely operated or autonomous vessels. In such cases, human factor analysis must transition from onboard crew to shore-based operators, introducing new challenges such as reduced situational awareness and cognitive overload. Therefore, future research should also focus on human factors associated with shore-based ship operation. Further development of grounding models is increasingly reflected in the use of regression analysis, which is a foundational concept in the field of machine learning. ML models aim to predict grounding risk by training regression algorithms using expert knowledge or historical data. A wide variety of regression techniques exist within ML, offering promising potential to uncover the complex interdependencies among grounding risk factors through big data. While these methods show strong predictive capabilities, their reliability remains highly sensitive to the quality of training data and the underlying data generation models.

From this bibliographic review of existing literature on grounding frequency and probability, it can be concluded that risk models are becoming increasingly sophisticated, requiring a growing number of input parameters. Nevertheless, the systematization of the literature presented in this paper offers a valuable framework for future research in grounding risk modeling, with the aim of achieving more accurate situational insight and contributing to improved safety in the maritime domain.

Despite providing a structured overview of the models developed to estimate ship grounding frequency, this paper has some limitations. The analysis relies exclusively on publicly available literature indexed in major databases such as Web of Science, Scopus, and Google Scholar, which may have excluded relevant gray literature or industry-specific reports. The bibliometric analysis was limited to the scope and quality of metadata available at the time of the search, which may affect the completeness of identified research clusters. Furthermore, the comparison of models was qualitative in nature, without a unified quantitative framework for evaluating their predictive performance or applicability in different maritime regions.

In terms of research gaps, several areas merit further investigation. There is a clear need for more empirical validation of grounding risk models using real-world data, particularly from underrepresented maritime regions. Moreover, integrating human factor modeling—especially for shore-based operators managing autonomous ships—remains an underexplored dimension. Another notable gap is the scarce application of adaptive, dynamic modeling approaches, such as online learning ML systems, that can respond in real time to evolving maritime traffic and environmental conditions. Lastly, future research should aim to develop and standardize evaluation frameworks for grounding prediction models, ensuring that their performance and applicability can be more consistently and objectively compared across studies. These gaps align with the broader goals of this paper, emphasizing the need for more reliable, flexible, and human-aware grounding risk models to advance maritime safety.

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