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A bibliometric review

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Review

Research on risk, safety, and reliability of autonomous ships: A bibliometric review

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ABSTRACT

The safety and reliability of autonomous ships are critical for the successful realization of an autonomous maritime ecosystem. Research and collaboration between governments, industry, and academia are vital in achieving this goal. This paper conducts a bibliometric review of the research on the risk, safety, and reliability of autonomous ships aiming to provide researchers and maritime stakeholders with a structured overview of the topics, development trends, and collaboration networks in this research field. 417 papers published between 2011 and 2022 were identified covering 940 authors, 31 countries, and 227 journals. Three main themes were determined in this research domain: “safety engineering and risk assessment for decision making”, “navigation safety and collision avoidance”, and “cybersecurity risk analysis”. Meanwhile, it was identified that research on cybersecurity in autonomous shipping is moving to overlap with safety, which requires future co-analysis methods. Additionally, the analysis of the most cited 30 papers suggests that further research is needed in the topics of unmanned machinery operation risks, online risk tools, system-theoretic safety analysis, human factor, and the determination of suitable risk acceptance criteria for safety assessment of autonomous ships. Furthermore, the analysis revealed that the development of unambiguous COLREGs regulation is crucial for the development of safe collision avoidance algorithms for MASS.

It was identified that the publication by Fan et al., (2020) is a key publication in this research field, while the journals of Ocean Engineering, Reliability Engineering & System Safety, and Safety Science are the key journals publishing on autonomous ship safety and reliability.

1. Introduction

In recent years, the idea of autonomous and unmanned ships has emerged as a potential solution for enhancing the efficiency and safety of maritime transportation (Negenborn et al., 2023). In 2012, the MUNIN project was launched as the first European initiative to explore the feasibility of unmanned and autonomous ships (Rødseth and Burmeister, 2012). On the other hand, the International Maritime Organization (IMO) started the Maritime Autonomous Surface Ship (MASS) regulatory scoping exercise in 2018 as a first step towards regulating autonomous ship design and operation (IMO, 2021). As a result, autonomous ships have received significant attention in the last decade and several other projects have been since then established to study different aspects related to autonomous ships (Bolbot et al., 2020; Kongsberg, 2017; Mørkrid et al., 2023; Oceanautonomy, 2020; Rolls Royce, 2016). Therefore, a growing number of studies has been published by different institutions that cover technical, operational, and legal aspects of ship autonomy (Chae et al., 2020; Hannaford et al., 2022; Madsen et al., 2022; Torben et al., 2023). While several maritime stakeholders are looking from the efficiency and profitability angle of autonomy, achieving these objectives still depends on ensuring safety (Chaal et al., 2022; de Vos et al., 2021; Hoem et al., 2019; Størkersen, 2021). In this respect, numerous studies emphasized that research on the safety and reliability of autonomous ships is substantial to achieve the aim of maritime policy-makers for safer and more efficient future shipping (BahooToroody et al., 2022b; Bolbot et al., 2021). Due to the importance of autonomous ships’ safety for different stakeholders, and about a decade after establishing the MUNIN project, this paper conducts a bibliometric review of the academic literature on the specific topic of risk, safety, and reliability of autonomous ships.

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Bibliometric review is a technique that identifies insightful information about the publication history and the trends in the development of a specific field of research (Aria et al., 2020; Umeokafor et al., 2022). As the number of scientific publications on a specific research topic is usually massive, a bibliometric review offers a systematic, transparent, and reproducible process to help researchers perceive the essential dimensions of interest (van Nunen et al., 2018; Yang et al., 2019). However, in the general field of autonomous shipping, only a few bibliometric reviews exist in the literature. Bogusllwski et al., (2022) have conducted a scientometric analysis of the research on situational awareness of autonomous vehicles from different smart transportation systems. As a part of this study, the authors also considered the hydrodynamics, logistics, and situational awareness of underwater and marine surface autonomous vehicles. Munim and Haralambides (2022) carried out a brief bibliometric review of the advances in technologies for MASS. The authors focused on analysing the technical research related to autonomous shipping as a part of the special issue in maritime economics and logistics. Razmjooei et al., (2023) conducted a bibliometric review of the literature on maritime industry 4.0. The study presented diverse dimensions of digitalization in the maritime sector and pointed out that autonomous ships have critical challenges requiring further exploration.

On the other hand, different systematic review studies have focused on the safety of autonomous ships. For instance, Veitch and Andreas Alsos (2022) reviewed the research studies on human-AI interaction in autonomous ships and concluded that such an interaction would affect safety and introduce new risks to ship systems. Johansen and Utne, (2020) reviewed the risk analysis method that can be used to enhance the System Theoretic Process Analysis (STPA) for autonomous ship applications. Thieme et al., (2018) reviewed the existing risk models and assessed their applicability to MASS. The authors emphasized that a compound risk model is needed to assess MASS risks and ensure their safety effectively. Zhou et al., (2020) reviewed the hazard analysis techniques and evaluated their suitability for autonomous ships. Basnet et al., (2020) reviewed and compared the system modelling techniques suitable for risk assessment integration in the case of autonomous ships. Montewka et al., (2018) reviewed and discussed the potential of applicable methods for the risk-based design of autonomous ships. Wróbel et al. (2021) reviewed the literature to identify the leading safety indicators to consider for collision avoidance, communication, and intact stability of autonomous ships. From a cyber-security risk perspective, Tusher et al., (2022) reviewed the literature to identify the highest cyber-security threats for autonomous ships and proposed a method to assess the related risks properly. Bolbot et al., (2022) presented a bibliometric review of the research on autonomous ship cybersecurity and concluded that the development of intrusion detection tools for cyber-attacks and effective techniques for cyber risk assessment are substantial for researchers in this field. Ellefsen et al., (2019) conducted a systematic literature review on the reliability of autonomous ship systems, focusing on prognostic and health management using deep learning methods. From a navigation safety perspective, different studies reviewed the path planning algorithms and methods to avoid collision accidents in autonomous ships (Huang et al., 2020; Öztürk et al., 2022; Vagale et al., 2021; Zhang et al., 2021).

While these reviews have contributed significantly to the advances in the research field of autonomous ship safety, the contribution of a bibliometric review in the same area is still missing to date, which was also pointed out by Tavakoli et al., (2023). Therefore, the present study attempts to fill the research gap and present a structured analysis of the characteristics of the literature on risk, safety, and reliability of autonomous ships during the past eleven years. As such, the primary goal of this study is to assist researchers, maritime policymakers, and funding agencies in identifying the most recent advancements and potential research directions, as well as effective resource allocation. Additionally, this study seeks to aid in identifying viable future collaborations for meeting their needs, especially in light of the imperative need for such partnerships to develop maritime policies that can effectively respond to the potential disruptions posed by autonomous ships, as reported by de Klerk et al. (2021).

2. Methodology

The method we follow in this study is adapted from the bibliometric analysis procedure and best practice guidelines summarized by Donthu et al. (2021). The procedure originally includes four major steps: defining the study aim and scope, choosing the bibliometric analysis techniques, collecting data, as well as performing the bibliometric analysis and reporting the results. This process has been frequently applied by many existing bibliometric reviews in diverse fields, such as van Nunen et al. (2018), Yang et al. (2019), Merigó et al. (2019), Gil et al. (2020), Bautista-Bernal et al. (2021), Gou et al. (2022), Luo et al. (2022), Umeokafor et al. (2022). In this section, the bibliometric review procedure for this study is elaborated on and illustrated in Fig. 1.

In the Pre-data collection phase, the aim and scope of this study are first defined. This bibliometric review is aimed at providing an overview of the research landscape on the topic of risk, safety, and reliability of autonomous ships over the past eleven years, thus the scope covers the scientific publications from January 1, 2011, to December 31, 2022. The objective of this study is to examine the impact of academic profiles and evaluate the performance of different journals, organizations, and countries, as well as their established collaborations. Additionally, the study identifies current research topics in the risk, safety, and reliability of autonomous ships and provides insights into unsolved challenges and future research directions.

We employ quantitative analysis of bibliometric information to observe the research performance through science maps. Furthermore, we selected the R programming language and the Bibliometrix SHINY application as the bibliometric analysis technique to aggregate research records from multiple databases with different data formats. Additionally, we perform a deeper content analysis of the most influencing publications to provide a thorough understanding of the specific topics and methods, as well as future research directions.

Step I is a preliminary step that precedes the extraction of scientific data records. The initial search for pertinent literature is executed through the use of diverse keywords in numerous scientific databases, including Google Scholar, Scopus, and Web of Science (WoS). Based on the outcomes of the initial search, it has been determined that the combination of Scopus and WoS is the most proficient. Specifically, Scopus and WoS jointly encompass all the high-quality publications present in Google Scholar, whilst their data file formats have more comprehensive and comparable bibliometric data. This makes Scopus and WoS more efficient for data analysis and informative results interpretation.

In order to extract the relevant research documents for the topic of autonomous ship risk, safety, and reliability, the keywords are adjusted according to the results until a final set of keywords is identified. The final set of keywords, applied to the title, abstract, and keyword fields, is defined in Fig. 2.

The OR gates at the top of Fig. 2 denote that one of the keywords combinations in the three left boxes AND one of the keywords in the 4th box should exist in the publications Title, Abstract or Keywords. The content of the boxes in Fig. 2 was adjusted based on the results of the preliminary keywords search, which commenced with only the title words covering the scope of the study. Given the large variety of initial publications obtained, coupled with the omission of several renowned and influential studies on the risk, safety, and reliability of autonomous ships, modifications were made to the first three boxes in Fig. 2. The aim is to cover the various combinations of names and concepts given to autonomous ships. Additionally, the keyword "unmanned surface vessels" was also considered due to its use in researching the safety and reliability of autonomous ships and its relevance as a case study/prototype for future ships (Glomsrud and Xie, 2019). Conversely, words

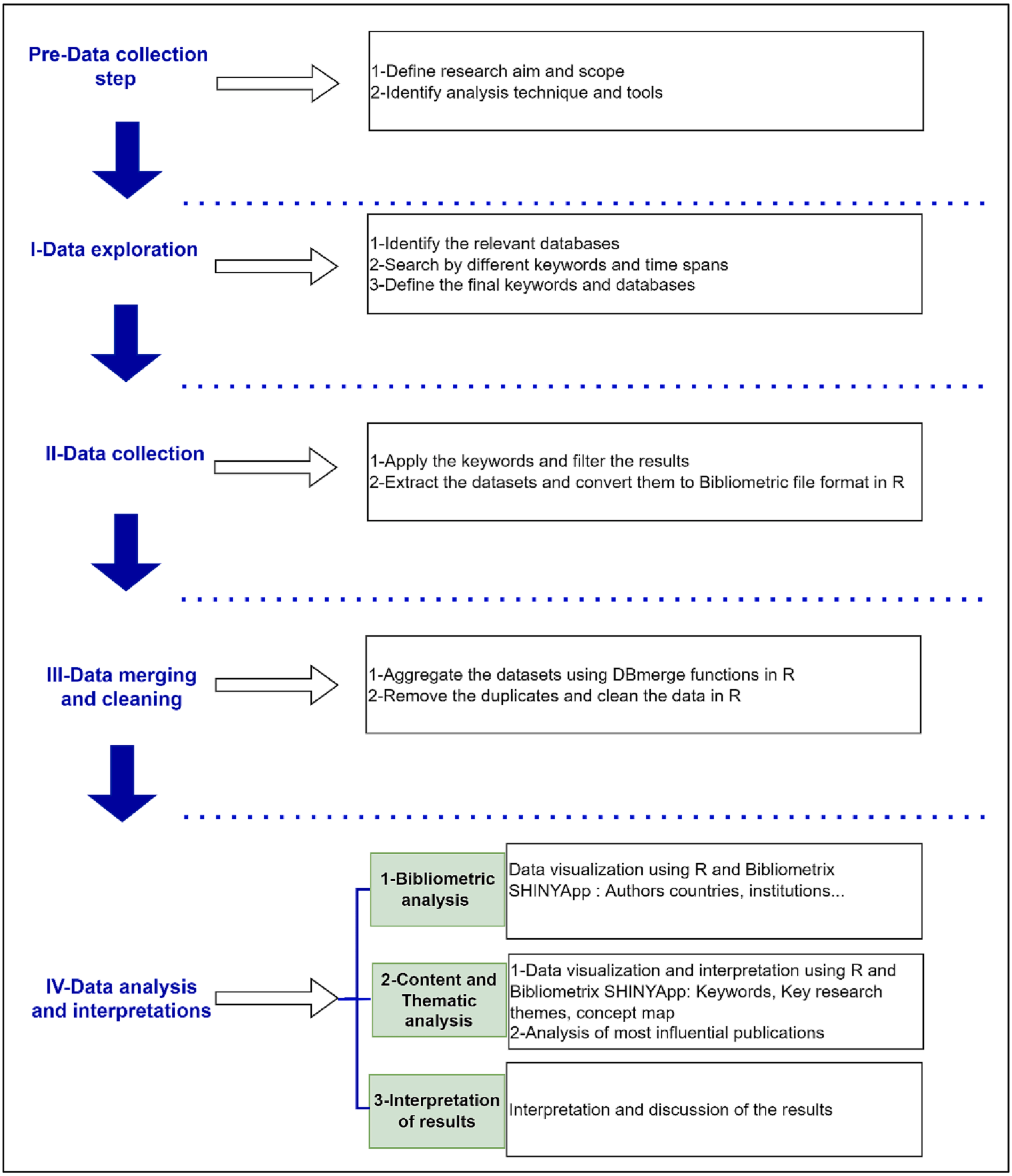

Fig. 1. Methodology workflow for the bibliometric review.

such as “Aerial,” “car,” and “underwater” were excluded to delimit the search domain to exclusively cover applications of autonomous ships. For the last box in Fig. 2, the same approach is applied. To refine the initial set of title keywords, the terms “hazard,” “failure,” and “accident” were incorporated, given the broad range of publications initially captured. It was discovered that several irrelevant studies utilized the terms “safety” or “risk” as generic expressions within the abstracts, even though these were not safety-focused studies. The term “hazard” was included in the keywords, as hazards represent specific conditions that contribute to risks. The term “reliability” was introduced, as reliability analysis involves failure analysis, with reliability referring to the ability of a system or process to operate without failure in fulfilling its intended function. Notably, accidents are often the result of single or multiple failures, or the convergence of single or multiple hazards.

In Step II, the keywords defined in Step I are used to extract the scientific records from both databases. Different filters are then applied in both databases to improve the quality of the dataset, such as limiting the results to articles, reviews, and conference papers from 01/01/2011

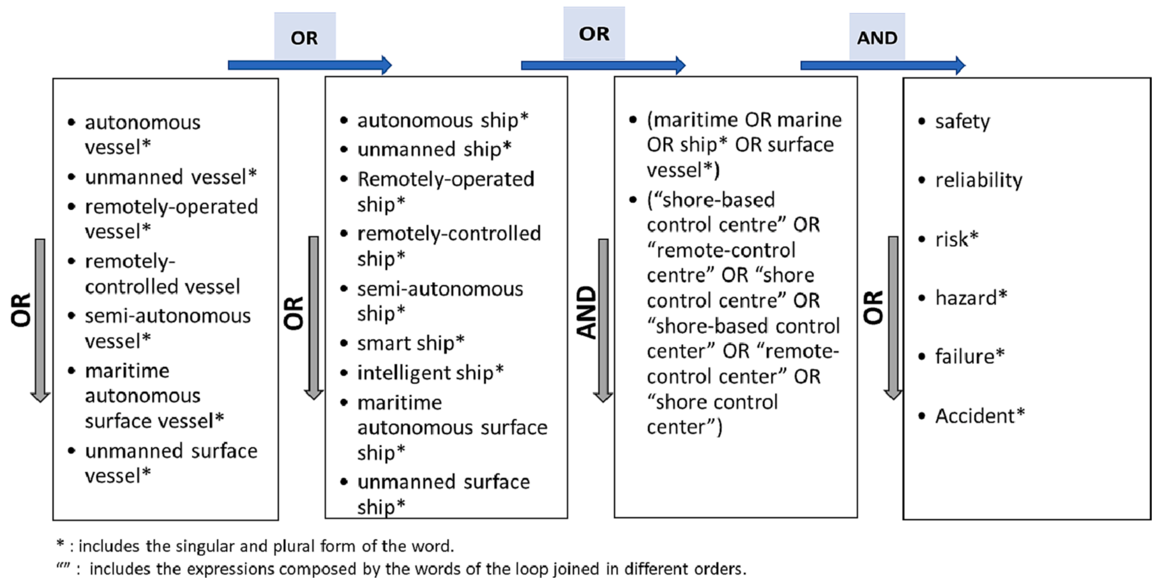

Fig. 2. Keywords set for searching in title, abstract and keywords fields.

until 31/12/2022 or limiting the language only to English. In addition, irrelevant subject fields such as medicine or chemistry are filtered. The subject field of Robotics Control was also excluded in order to limit the publications concerning USVs to safety-related studies. The extracted data is then converted into Bibliometrix file format using the data importing tool in the software application SHINY (Aria and Cuccurullo, 2017).

In Step III, the columns of both files are adjusted to have the same set of columns. The datasets from both databases are then aggregated using the R programming function "DBmerge", which also removes the duplicates automatically. Furthermore, R programming is also used to clean the data (such as editing the authors' and institutions' names written in different spellings) and to pre-process the data.

In step IV, the clean final dataset is processed to analyse the bibliographic data using the selected R programming tools. The same tools are used to visualize the essential bibliometric and thematic analysis results in science maps, which are further analysed to interpret the informative trends and features and derive relevant conclusions. Additionally, a more in-depth analysis is conducted on the most impactful publications to extract crucial information on unresolved safety challenges and identify potential areas for future research.

3. Results and discussion

3.1. Datasets

The outcome of the final keywords search included 657 scientific research papers, 414 in WoS, and 243 in Scopus. After the conversion of the files and the unifying of the format of the datasets, 240 duplicated documents in both datasets were identified and automatically eliminated. This task made the used final dataset comprehensive as it contains accurate records from WoS and Scopus. As a common approach, researchers often extract data from only one of the common research databases, WoS or Scopus and use the VOSviewer software tool (van Eck and Waltman, 2014) to visualize the results (Li et al., 2021). This is probably due to the challenge of processing data files with different formats, requiring manual processing of data files from different databases, which is both time-consuming and error-prone. However, extracting the records from only one of these databases can significantly limit the scope of our analysis and affect the comprehensiveness of its results (Bogusllwski et al., 2022; Gil et al., 2020).

Table 1 illustrates an information summary of the final publications composed of the aggregated WoS and Scopus datasets.

Table 1
Main information about the collection.

Description	Results
MAIN INFORMATION ABOUT DATA	
Timespan	01–01-2011:31–12-2022
Sources (Journals, Books, etc)	227
Documents	417
Annual Growth Rate %	43.59
Document Average Age (per year)	3.36
Average citations per doc	9.71
References	12,980
AUTHORS	
Authors	940
Authors of single-authored docs	34
AUTHORS COLLABORATION	
Multi-authored docs	381
Single-authored docs	36
Average number of co-Authors per Doc	3.75
International co-authorships %	10.55
DOCUMENT TYPES	
article	251
article; book chapter	1
conference paper	97
proceedings paper	62
review	6

3.2. Bibliometric analysis

3.2.1. Publication growth trends and sources

The results in the databases showed that research on the risk, safety, and reliability of autonomous ships started to appear in the research agenda in 2011. For this reason, the final dataset considers the timespan between 2011 and 2022. The number of peer-reviewed research publications is an indicator used to monitor the development pattern of a scientific research field (Price, 1963). The annual growth rate of scientific production in this field over the past eleven years is 43.59% (Table 1), which gives an idea about a blooming research field. Annual growth rate refers to the yearly growth of publication number (in percentage) averaged over the eleven years of the timespan. Fig. 3 gives us a preview of the peer-reviewed publication numbers in autonomous ship safety and reliability. According to Price's law (Dabi et al., 2016), the growth of a research domain goes through four stages: (i) precursor

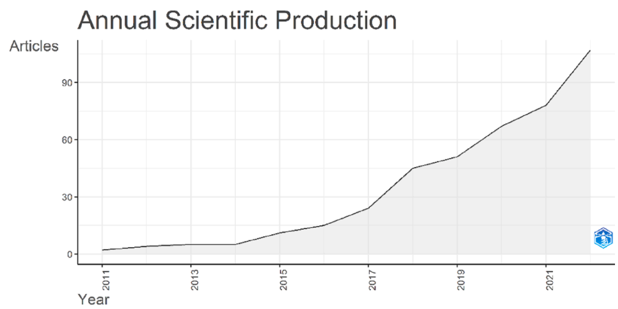

Fig. 3. Annual scientific production from 01/01/2011 to 31/12/2022.

phase, when a small number of scientists published in the new field, (ii) exponential growth stage, when the number of researchers interested in the field increases, (iii) consolidation of the body of knowledge stage and (iv) the decrease in the number of publications stage.

Fig. 3 shows that until 2016, the number of publications has always been below 15 each year. The publication rate experienced a dramatic upsurge in 2016, which is likely due to the propagation of results of the first autonomous ship projects. This growth in the scientific literature indicates that the field of safety and reliability of autonomous ships is at the stage of constant exponential growth. This also shows that the concern about autonomous ship safety from academia, industry, and policymakers increased since the culmination of the feasibility studies covered in the first large projects related to autonomous ships.

The sources of publications on the topic of risk, safety and reliability of autonomous ships are 251 in total. Fig. 4 presents the ranking of the ten most active sources by their total number of publications in this research field. Ocean Engineering is the leading journal, with a total number of 42 scientific publications.

Although the number of publications is a key indicator of the scientific activity of journals, this indicator is not the only one to consider (Aria et al., 2020). The scientific impact is another important indicator because it indicates the impact of the publications and the importance of the covered sub-topics.

Fig. 5 illustrates the impact of the top ten scientific publication sources in the field of risk, safety, and reliability of autonomous ships. The impact is calculated with the H-index of the source. The index is automatically computed for the dataset under the Bibliometrix Shiny App. The H-index of a journal is equal to h if at least h publications in the journal were cited h times or more (Aria and Cuccurullo, 2017; Hirsch, 2005).

Fig. 5 shows that the journal of Ocean Engineering is still leading and has the highest scientific impact. Compared to Fig. 4, Fig. 5 shows that the journal of Reliability Engineering and Systems Safety, and the journal of Safety Science have both a higher scientific impact than the journal of Marine Science and Engineering and IEEE Access, although with a fewer number of publications. The journals, Reliability Engineering and Systems Safety, and Safety Science are dedicated to the fields of safety and reliability. Hence, they offer a compelling and robust alternative to researchers investigating the safety of autonomous ships, which explains their higher scientific impact in this field.

Figure 6 presents the growing trend of the top five journals ranked by the number of publications. As seen in the figure, starting from mid-2021, the Journal of Marine Science and Engineering has experienced the highest growth rate compared to the other journals and changed from rank 5 to rank 2 in 2021. Figure 6 shows also that the journal of Safety Science has experienced a decline in publications growth starting from mid-2020 to reach a competition level (at the overlap in 2021) with the journal of Reliability Engineering and Systems Safety in 2021. The Ocean Engineering journal outperforms all other journals regarding the number of publications except in mid-2020 when the journal of Safety Science was leading. Consequently, the topic of safety and reliability of autonomous ships is progressing also in journals covering maritime topics and not only those specialized in risk, safety, and reliability.

3.2.2. *Analysis of citations and authors' collaborations*

A total of 940 authors produced the 417 publications present in the dataset. Only 36 of these publications (8.63%) were written by (34) single authors. On the other hand, the average number of co-authors who collaborated in the remaining 381 publications (91.36%) is 3.75. Collaboration among the co-authors on the autonomous ship safety and reliability research topic is clearly substantial, as the multi-authored publications account for over 90% of the total number of publications. This high percentage of publications with multiple co-authors also indicates a potential for future collaboration opportunities (Wang et al., 2014).

The collaboration dynamics among the co-authors are analysed using the collaboration network map, and the results are shown in Fig. 7. The edges between the nodes in Fig. 7 represent the collaboration strength between different co-authors on the topic of the safety and reliability of autonomous ships. The thickness of the edges gives an idea of the strength of collaboration between the interlinked nodes. The nodes of the network represent the authors. The bigger the node is, the higher number of articles the author has co-authored. On the other hand, the colours represent the collaboration clusters, which generally depict the researchers' close network.

Particularly, the network includes four significant clusters with solid and numerous collaboration activities: the Red, the Blue, the Purple, and the Grey clusters. It is noteworthy that the researchers within the Blue and the smaller Orange and Brown clusters are mainly from Chinese

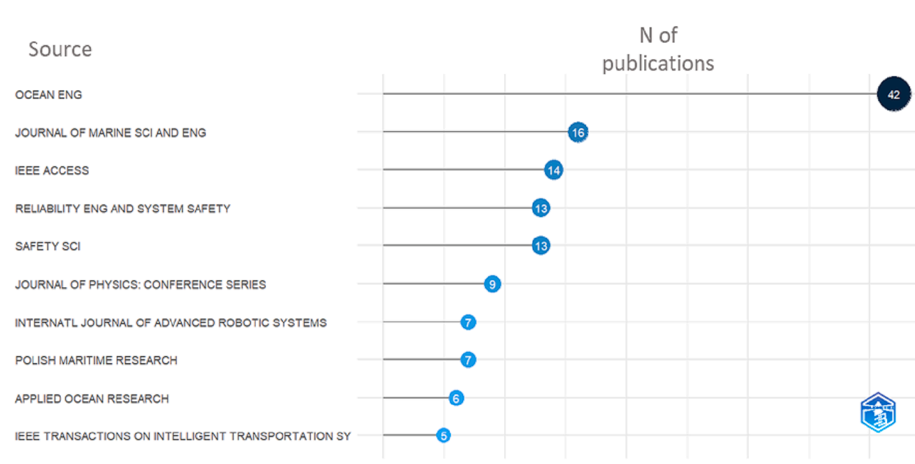

Fig. 4. The ten leading sources ranked by their number of publications.

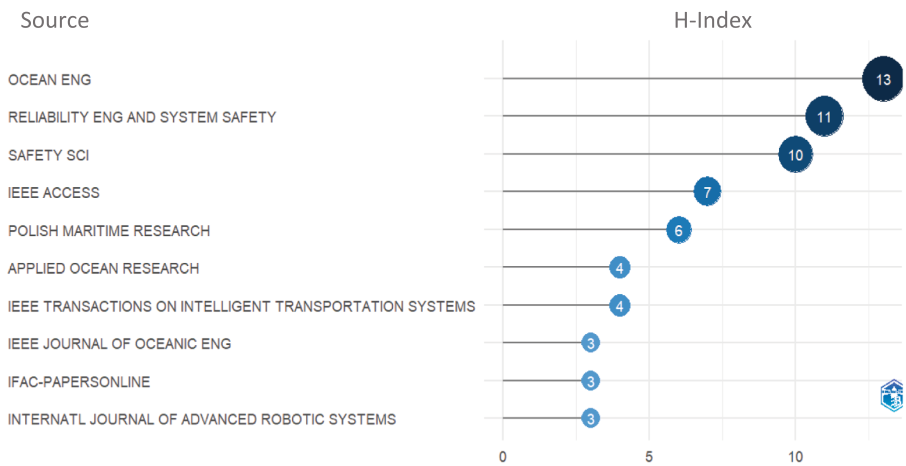

Fig. 5. The ten leading sources ranked by their H-index.

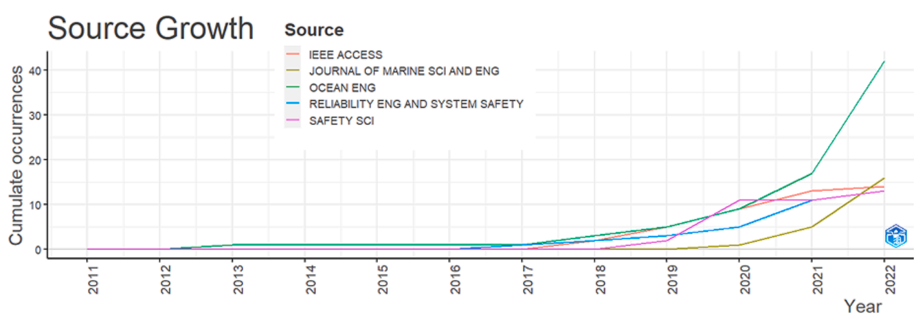

Fig. 6. Sources' growth trend

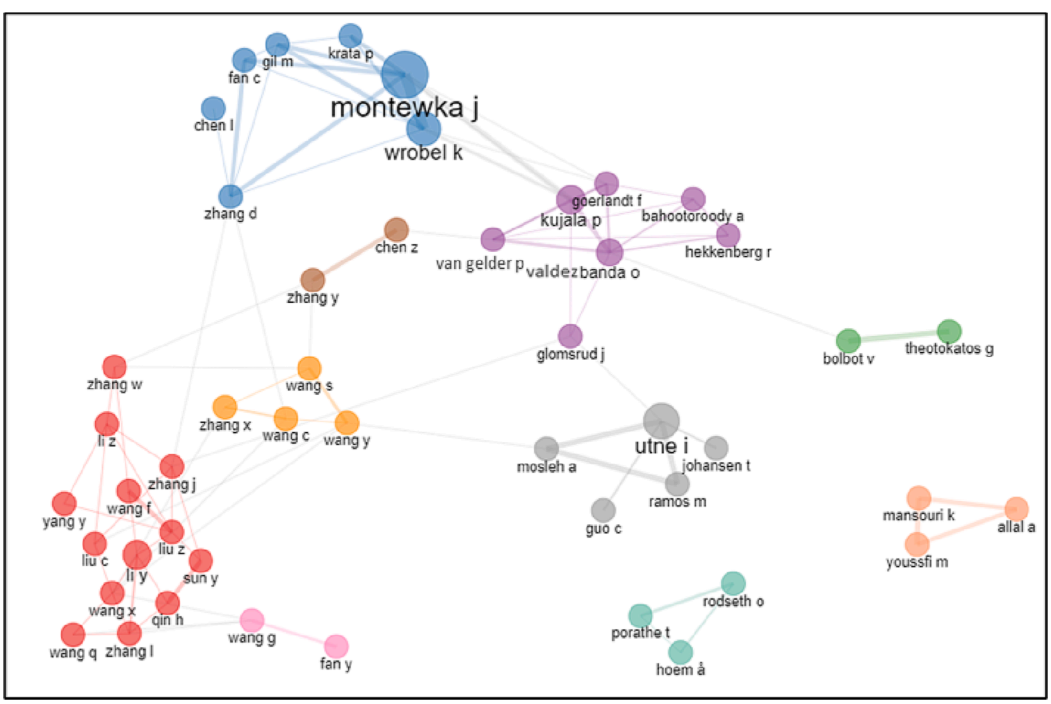

Fig. 7. Authors' collaboration network.

Table 2
The top 30 publications ranked by average total citations per year.

Rank	Title	Author and year of publication	Journal	Employed method	TC per Year	Total Citations	H-index of lead author
1	A framework to identify factors influencing navigational risk for Maritime Autonomous Surface Ships	(Fan et al., 2020)	Ocean Engineering	4P4F	42.50	85	3
2	Deep learning for autonomous ship-oriented small ship detection	(Chen et al., 2020)	Safety Science	Neural Networks	39.50	79	4
3	Risk assessment of the operations of maritime autonomous surface ships	(Chang et al., 2021)	Reliability Engineering & Systems Safety	Failure Modes and Effects Analysis (FMEA) + Bayesian Networks (BN)	37.50	75	1
4	A probabilistic model of human error assessment for autonomous cargo ships focusing on human–autonomy collaboration	(Zhang et al., 2020)	Safety Science	Technique for Human Error Rate Prediction + BN	37.00	74	5
5	Towards the assessment of potential impact of unmanned vessels on maritime transportation safety	(Wróbel et al., 2017)	Reliability Engineering & Systems Safety	Accident reports analysis	33.80	169	9
6	Finite-time distributed formation control for multiple unmanned surface vehicles with input saturation	(Huang et al., 2021)	Ocean Engineering	Ship navigation control	33.00	33	2
7	Collision avoidance on maritime autonomous surface ships: Operators' tasks and human failure events	(Ramos et al., 2019)	Safety Science	Hierarchical Task Analysis	32.33	97	5
8	Ship collision avoidance and COLREGS compliance using simulation-based control behavior selection with predictive hazard assessment	(Johansen et al., 2016)	IEEE Transactions on Intelligent Transportation Systems	Navigation risk assessment	30.17	181	6
9	Autonomous vessels: state of the art and potential opportunities in logistics	(Gu et al., 2021)	International Transactions in Operational Research	Review	30.00	30	1
10	The Impact of Autonomous Ships on Safety at Sea – A Statistical Analysis	(de Vos et al., 2021)	Reliability Engineering & Systems Safety	Accident reports analysis	30.00	30	2
11	Deep reinforcement learning-based collision avoidance for an autonomous ship	(Chun et al., 2021)	Ocean Engineering	Ship navigation control	30.00	30	1
12	A concept of critical safety area applicable for an obstacle-avoidance process for manned and autonomous ships	(Gil, 2021)	Reliability Engineering & Systems Safety	Navigation risk assessment	27.00	27	5
13	USV Formation and Path-Following Control via Deep Reinforcement Learning with Random Braking	(Zhao et al., 2021)	IEEE Transactions on Neural Networks and Learning Systems	Ship navigation control	27.00	27	1
14	Towards supervisory risk control of autonomous ships	(Utne et al., 2020)	Reliability Engineering & Systems Safety	System Theoretic Process Analysis + BN	24.33	73	8
15	A systemic hazard analysis and management process for the concept design phase of an autonomous vessel	(Valdez Banda et al., 2019)	Reliability Engineering & Systems Safety	STPA	22.33	67	5
16	Towards the development of a system-theoretic model for safety assessment of autonomous merchant vessels	(Wróbel et al., 2018)	Reliability Engineering & Systems Safety	STPA	22.00	88	9
17	A multinomial process tree for reliability assessment of machinery in autonomous ships	(Abaei et al., 2021)	Reliability Engineering & Systems Safety	Ship reliability	22.00	22	2
18	Human-system concurrent task analysis for maritime autonomous surface ship operation and safety	(Ramos et al., 2020)	Reliability Engineering & Systems Safety	Event Sequence Diagrams + Concurrent Task Analysis	20.67	62	5
19	A real-time collision avoidance learning system for Unmanned Surface Vessels	(Zhao et al., 2016)	Neurocomputing	Navigation risk assessment	20.33	122	3
20	A framework to model the STPA hierarchical control structure of an autonomous ship	(Chaal et al., 2020)	Safety Science	STPA	19.50	39	2
21	System-theoretic approach to safety of remotely-controlled merchant vessel	(Wróbel et al., 2018)	Ocean Engineering	STPA	19.25	77	9
22	Path Following Control of the Underactuated USV Based On the Improved Line-of-Sight Guidance Algorithm	(Liu et al., 2017)	Polish Maritime Research	Ship navigation control	18.67	56	2
23	Distributed model predictive control for vessel train formations of cooperative multi-vessel systems	(Chen et al., 2018)	Transportation Research Part C: Emerging Technologies	Ship navigation control	18.00	72	3
24	Collision risk measure for triggering evasive actions of maritime autonomous surface ships	(Huang and van Gelder, 2020)	Safety Science	Navigation risk assessment	18.00	36	3
25	Assessing ship risk model applicability to Marine Autonomous Surface Ships	(Thieme et al., 2018)	Ocean Engineering	Review	17.50	70	3
26	Adaptive trajectory tracking algorithm of unmanned surface vessel based on anti-windup compensator with full-state constraints	(Qin et al., 2020)	Ocean Engineering	Ship navigation control	17.33	52	4
27	Multi-attribute decision-making method for prioritizing maritime traffic safety influencing factors of autonomous ships' maneuvering decisions using grey and fuzzy theories	(Xue et al., 2019)	Safety Science	Navigation risk assessment	17.33	52	2
28	Application of optimal control theory based on the evolution strategy (CMA-ES) to automatic berthing	(Maki et al., 2020)	Journal of Marine Science and Technology	Ship navigation control	16.50	33	2
29	Maritime Autonomous Surface Ships from a risk governance perspective: Interpretation and implications	(Goerlandt, 2020)	Safety Science	Risk governance	15.50	31	4
30	Autonomous shipping and its impact on regulations, technologies, and industries	(Kim et al., 2020)	Journal of International Maritime Safety, Environmental Affairs, and Shipping	Review	13.50	27	1

universities, which shows a solid national collaboration in China. It is also notable that the Purple node of Van Gelder.P seems to be an essential link between the Purple and the Brown clusters, although the affiliation of Van Gelder.P is the Delf University of Technology. This means that Van Gelder.P represents an active international collaborator between the Purple, the Red and the Purple clusters. Similarly, the purple node of Glomsrud.J and the grey node of Mosleh.A are active international collaborators acting as a link between the Orange cluster and the Purple and Grey clusters respectively. Moreover, the network analysis indicates that a majority of researchers within each cluster exhibit substantial collaboration among their respective groups as well as with researchers belonging to other clusters. This finding further consolidates the existence of a relatively robust research collaboration network in the domain of safety and reliability of autonomous ships, which aligns with the observed co-authorship percentages in this field. Notwithstanding, certain researchers, such as those affiliated with the Green Mint cluster (mainly associated with Rodseth O) and the orange cluster (mainly associated with Youssfi M), exhibit more frequent collaboration within their own clusters but relatively infrequent collaboration with researchers from other clusters.

Generally, the authors' collaboration network shows that the nodes of the author Montewka.J, Wrobel.K, Li.Y, Utne.I, Kujala.P, and Valdez Banda, O, are relatively big-sized. This implies that these researchers are engaged in a comparatively high level of collaboration pertaining to the subject of autonomous ship safety and reliability.

Authors might have many co-authored publications, while their primary contribution to the field stems from their publications as lead authors. There is a general assumption that the number of citations is the indicator of the scientific contribution of an article (Smith, 2007; Ugolini et al., 2015). However, the number of citations of a single publication is growing over time. This makes the ranking of publications' impact based solely on the number of citations without considering the publication year, a piece of misleading information. For this reason, the 30 most influential publications on the safety and reliability of autonomous ships were extracted and ranked by the total number of citations per year. The results are presented in Table 2, which shows that the average number of citations per year for the most influencing papers on autonomous ship safety and reliability ranges from 42.5 to 13.5. The most impactful paper was "A framework to identify factors influencing navigational risk for Maritime Autonomous Surface Ships", written by Fan et al., in 2020 and has had 85 citations.

The last column in Table 2 shows the H-index of the first authors of the top 30 publications. The H-index is calculated automatically in the R SHINY App based on the total number of publications and citations of the author within the analysed dataset. The author's H-index is equal to h if at least h of his/her papers (both as lead author and co-author) have been cited more than h times (Aria and Cuccurullo, 2017; Hirsch, 2005).

As given in Table 2, among the first authors of the top 30 publications, Wróbel Krzysztof has the highest impact with an H-index of nine. This correlates with the fact that Wróbel has three impactful articles among the top 30 publications. It is noteworthy that Wróbel Krzysztof and Ingrid Bouwer Utne's high H-index is owed to their other publications within the dataset, in addition to those in Table 2. Table 2 shows also that the publication sources "Journal of Reliability and Systems Safety" and the "Journal of Safety Science" have the highest number of top influencing articles (9/30) and (7/30) respectively. This bolsters the evidence that the journals, Reliability and Systems Safety, and Safety Science have the highest scientific impact on autonomous ship safety and reliability research, as covered in sub-section 3.2.1.

3.2.3. *Countries and institutions: Distribution and impact*

- Countries

Research publications on the safety and reliability of autonomous ships have originated from 31 countries distributed on all the continents except Antarctica. Table 3 shows the ten most productive countries in this topic of research. As presented in Table 3, more than 90% of the publications were produced by only three countries, China, the USA, and Norway. This might suggest that the research on autonomous ships' safety and reliability is the focus of a limited number of countries. Still, it can also be due to the narrow topic of interest as a subject of this study.

Table 3
Number of publications per country.

Rank	Country	N of documents	Percentage of the dataset
1	CHINA	262	62.83 %
2	NORWAY	76	18.23 %
3	USA	46	11.03 %
4	SOUTH KOREA	33	7.91 %
5	FINLAND	27	6.47 %
6	UK	26	6.24 %
7	POLAND	25	6.00 %
8	JAPAN	16	3.84 %
9	AUSTRALIA	15	3.60 %
10	NETHERLANDS	15	3.60 %

On the other hand, Table 3 shows that a single country has produced over 60% of the publications. This most productive country is China, with a total of 262 publications in the field of autonomous ship safety and reliability. It is widely recognized that the economic development of a country and its public policy affect its scientific production across most of the research domains (Liu et al., 2012). Thus, the seven most industrialized countries of the G7 (USA, Japan, Italy, Germany, UK, Canada, and France) are usually leaders in scientific production across domains. The main reason behind this is that G7 countries have development strategies targeting the research and sufficient resources to allocate for it (Yang et al., 2013). However, this seems to be different for the research on the safety and reliability of autonomous ships. Out of the G7 countries, only USA, UK and Japan are among the ten most productive countries. Different explanations can be inferred from this finding. It can be inferred that Italy, Germany, Canada, and France are focusing on patent-related research work or have more scientific publications in other languages than English, or they might not have autonomous shipping high on the agenda for their maritime policies.

Table 3 shows that the other most productive countries in autonomous ship safety and reliability are the traditional maritime nations such as Norway, South Korea, Finland, Netherlands, and Australia. These countries have historically concentrated their maritime policies around ship design and/or seafaring. Nevertheless, Table 3 shows that the scientifically most productive country is China, which is known as a highly successful emerging economy (World Bank, 2022). Poland is also considered one of the next emerging economies currently under an economic rise phase (Krusling, 2022). Therefore, the result in Table 3 tells that ensuring the safety and reliability of autonomous ships might be a target development area in the Chinese and Polish maritime policies.

A more thorough analysis of the countries' scientific activity in the field of autonomous ship safety and reliability is given in Fig. 8. The result shows the scientific impact measured by the total number of citations and the average number of citations per document from each country among the list in Table 3. Fig. 8 shows that China has the highest number of total citations, 1162. It is also noticeable from Fig. 8 that Poland has the highest average article citations of 25.50, followed by Norway with 17.28 and the UK with 10.94.

To address another aim of bibliometric review hereby, international collaboration is investigated. The cooperation between the countries in the scientific field of autonomous ship safety and reliability was analysed using the "Country Collaboration Map" and the result is given in Fig. 9. The blue surfaces on the map denote the countries that have publications on the safety and reliability of autonomous ships. The darker the blue colour is, the more publications the country has. The orange links in the map denote the strength of scientific collaboration

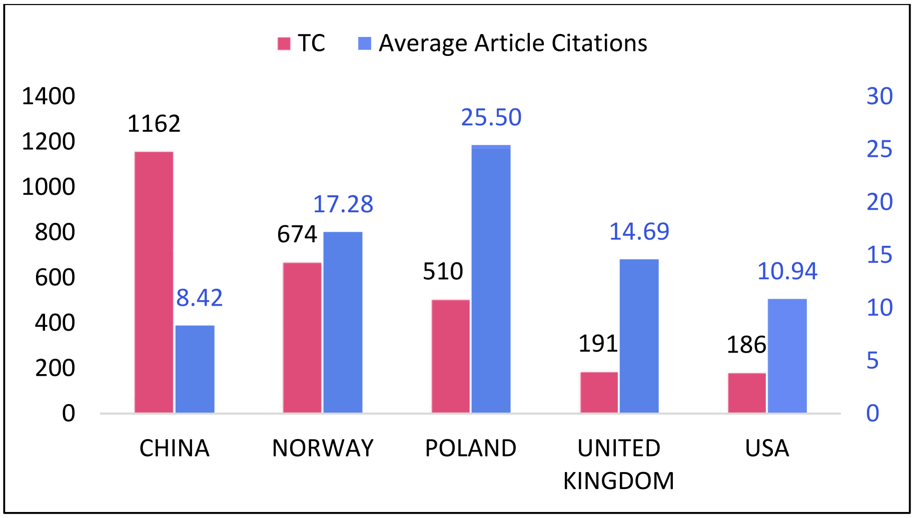

Fig. 8. Highest scientific impact per country.

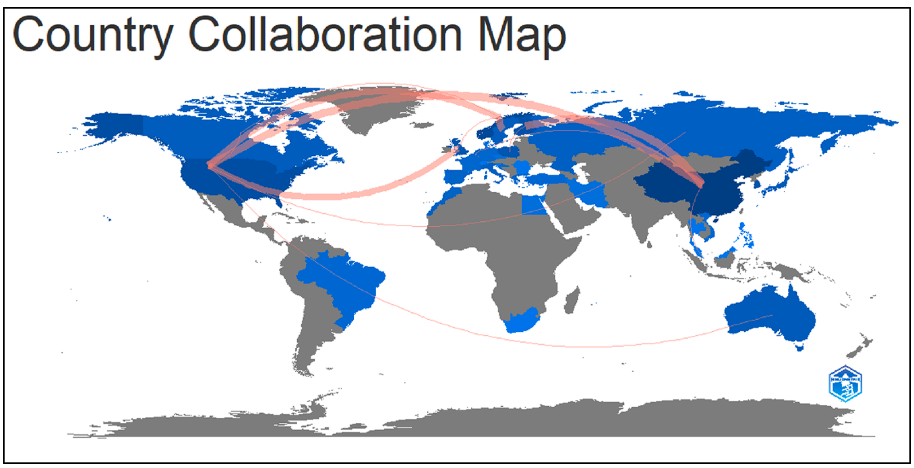

Fig. 9. Countries' collaboration map.

between countries. As noticed in Fig. 9, USA and China seem to have intense collaboration activities with various countries across different continents. The USA strongly collaborates with Northern Europe, the UK, and China. Similarly, China strongly collaborates with Northern Europe, Poland, and the Netherlands. Additionally, scientific collaboration seems to be active, but with less strength, between China and Australia, Australia, and USA, as well as Canada and Northern Europe. It is widely admitted that strong international collaborations are usually centred around the most productive countries, which has also been a common finding in other bibliometric reviews (Zheng et al., 2016).

On the other hand, Fig. 9 shows that the African continent has only a few countries active in the research field of safety and reliability: Morocco, Egypt, and South Africa. Similarly, Brazil is the only active country in Latin America in this field. However, neither Africa nor Latin America has solid international collaboration on this research topic. One striking result shown in the collaboration world map is that South Korea, the fourth most productive country in this research field, seems less active regarding international collaboration. Furthermore, the analysis presented in Fig. 9 demonstrates that Northern European countries, namely Norway and Finland, exhibit notable research leadership in the specific domain under investigation. However, it is noteworthy that there remains a relatively low level of collaborative efforts between these two countries, despite their geographical proximity.

Fig. 10 shows the results of a more detailed collaboration network that was generated to get deeper information concerning the collaboration between countries. The nodes in Fig. 10 represent the countries; the bigger the node is, the more international multi-authored papers the country has. The colours represent the clusters, which means close collaboration among a single cluster's nodes. As seen in Fig. 10, the clusters are centred around the most productive countries, consistent with what was noticed in Table 3. On the one hand, Central European countries form a cluster of collaboration between France and Italy. The cluster centred around the USA has many countries from different continents, which indicates that the USA has a diverse international collaboration. On the other hand, the cluster centred around China includes another country from the ten most productive countries: Finland. This cluster affirms also that Singapore has restricted its collaborations with foreign countries to solely China. The node of China has the biggest size, which means a higher number of international multi-authored publications within this cluster and others.

The strength of the links between two nodes in Fig. 10 represents the strength of collaboration between the corresponding countries. Another observation inferred in Fig. 10 is that Poland and Finland, which belong to two different clusters, have strong collaboration links. The same applies to Canada and China, Sweden, and Norway, which are from different clusters but have strong collaboration links. Interestingly, the results in Fig. 10 confirm those shown in Fig. 10; South Korea seems less internationally active in collaboration. Therefore, given the discussed findings from the map presented in Fig. 10 and the network in Fig. 10, it can be concluded that there is a potential for more international

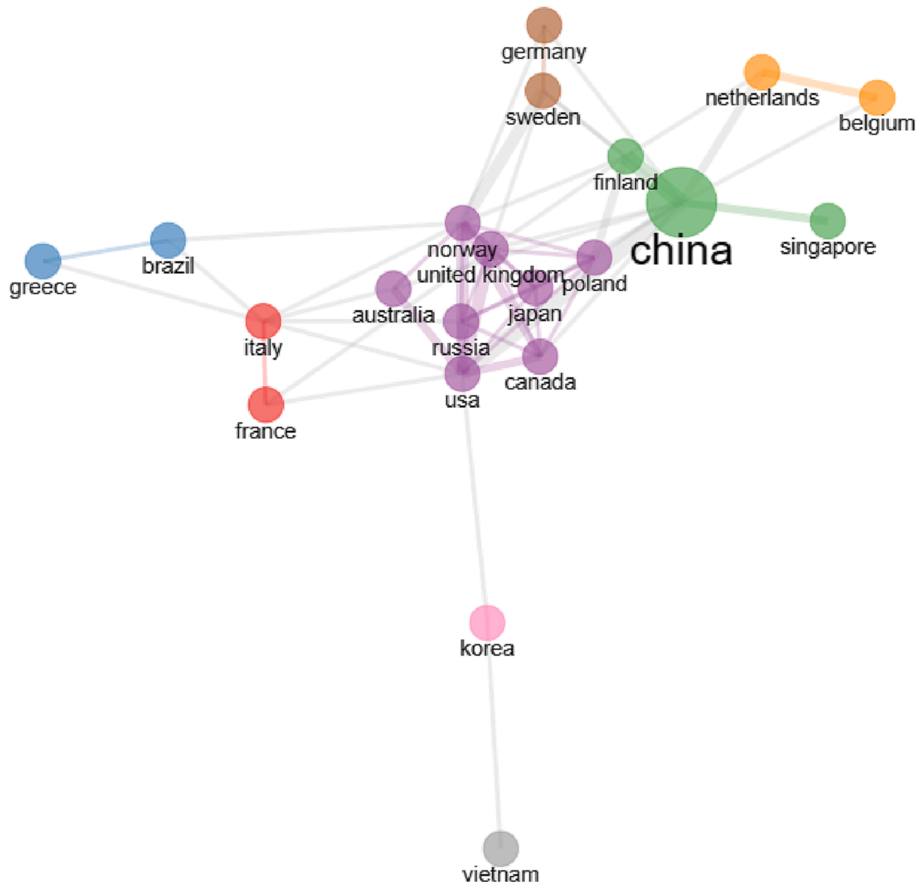

Fig. 10. Countries' collaboration network.

collaboration between South Korea, the active countries in Latin America as well as the African continent, with the rest of the world. In addition, European countries from the G7, such as Germany, France, and Italy, could be attractive targets for international collaboration on autonomous ship safety and reliability. This is still conditioned on whether these countries will have autonomous shipping in their maritime policy and whether international cooperation interests them.

- Institutions

A closer look at the countries and an analysis of the authors' affiliations gives information about the active institutions in each country. According to the affiliation information, the 417 research papers on the safety and reliability of autonomous ships are produced by 242 affiliations, with the possibility that one author is affiliated to more than one research institution or that a paper is multi-authored from different affiliations. Table 4 shows the most productive institutions in this field of research.

Table 4
Highest number of publications per institution.

Rank	Affiliation	Country	N. Articles
1	WUHAN UNIVERSITY OF TECHNOLOGY	China	81
2	DALIAN MARITIME UNIVERSITY	China	63
3	NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY	Norway	36
4	AALTO UNIVERSITY	Finland	32
5	HARBIN ENGINEERING UNIVERSITY	China	32
6	GDYNIA MARITIME UNIVERSITY	Poland	23
7	UNIVERSITY OF STRATHCLYDE	United Kingdom	19
8	DELFT UNIVERSITY OF TECHNOLOGY	Netherlands	16
9	SHANGHAI MARITIME UNIVERSITY	China	16
10	UNIVERSITY OF SOUTH-EASTERN NORWAY	Norway	14

Table 4 supports the results discussed in the subsection above showing that the first and the second most productive institutions are Wuhan University of Technology and Dalian Maritime University, both located in China, which was previously ranked as the most productive country. Norwegian University of Science and Technology has the highest number of publications among European universities, followed by Aalto university in Finland and Gdynia Maritime University in Poland.

Fig. 11 shows the evolution trend in the scientific production of six institutions with the highest publication growth. The two Chinese universities, Wuhan University of Technology and Dalian Maritime University experienced exponential growth starting around 2019. These two universities outperformed all the universities, including Harbin Engineering University, which was the most productive university until 2018. The other three universities (Norwegian University of Science and Technology, Gdynia Maritime University, and Aalto University) have a close publication growth rate and are among the most productive European universities in the field of autonomous ship safety and reliability. It can be concluded from Table 4 and Fig. 11 that the scientific research on autonomous ship safety and reliability within these three universities and the Delft University of Technology in the coming years can be a game changer in Europe.

3.3. *Publication content and thematic analysis*

3.3.1. *Thematic and content analysis*

Analysing the content of the publications is conducted based on the

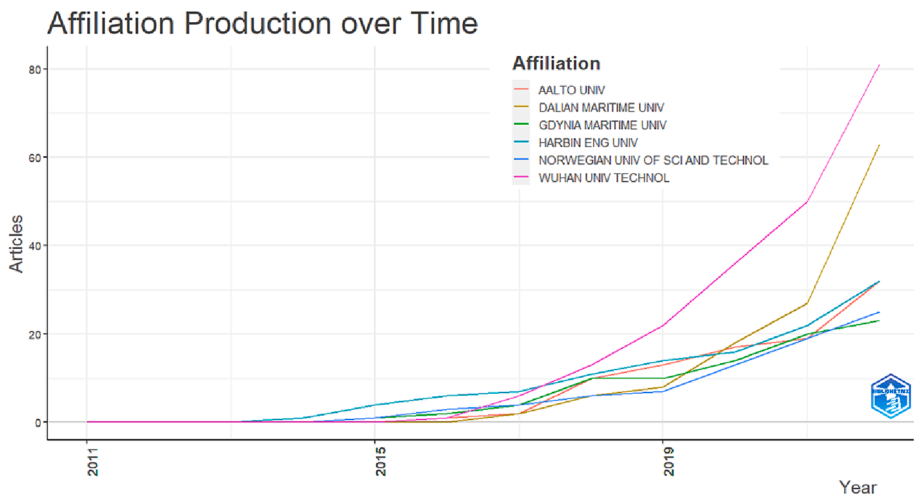

Fig. 11. Institutions' publication growth.

terms used in their titles and abstracts. The analysis of these terms can bring out the main topics of interest in the safety and reliability of autonomous ships plotted in a network format in Fig. 12. Before visualizing this result, the terms that were considered synonyms were merged into one term, such as "navigation" and "ship navigation", or plural and singular forms of the same word, such as "ship" and "ships". A threshold was also set to consider the terms mentioned in at least five publications; thus, only 70 terms are visualized in the network. In Fig. 12, the node size represents the frequency of the term's occurrence in the publications. The larger the node's size, the higher the occurrence frequency in the analysed publications dataset. The distance between the nodes represents the strength of their linkage. This means that a shorter link between two nodes represents a higher joint-occurrence frequency and, as a result, a stronger thematic connection between the corresponding nodes' terms (Aria and Cuccurullo, 2017). These terms are further clustered based on their corresponding research themes using different colours.

Fig. 12 shows three main clusters; the red cluster centred on risk assessment, the blue cluster centred on accident prevention, and the green cluster centred on tracking control. The red cluster includes other important sub-clusters as it has three other large nodes of Safety Engineering, Navigation, and Decision-Making.

The proximity of the nodes of "stpa", "uncertainty analysis", "risk perception", "bayesian network", and "fuzzy inference" to the risk assessment node indicates that this part of the red cluster pertains to studies that have performed risk assessments to communicate findings to stakeholders regarding the design and operation of autonomous vessels. Moreover, STPA, Fuzzy Inference and Bayesian Network appear as attractive methods for researchers in this field. On the other hand, the Navigation node, situated within the same red cluster, displays a close relationship with both the Collision Avoidance node and the Decision-Making node. Additionally, the Navigation node is in close proximity to the green cluster, which includes the themes of Tracking Control, algorithm development, and optimization models. This association

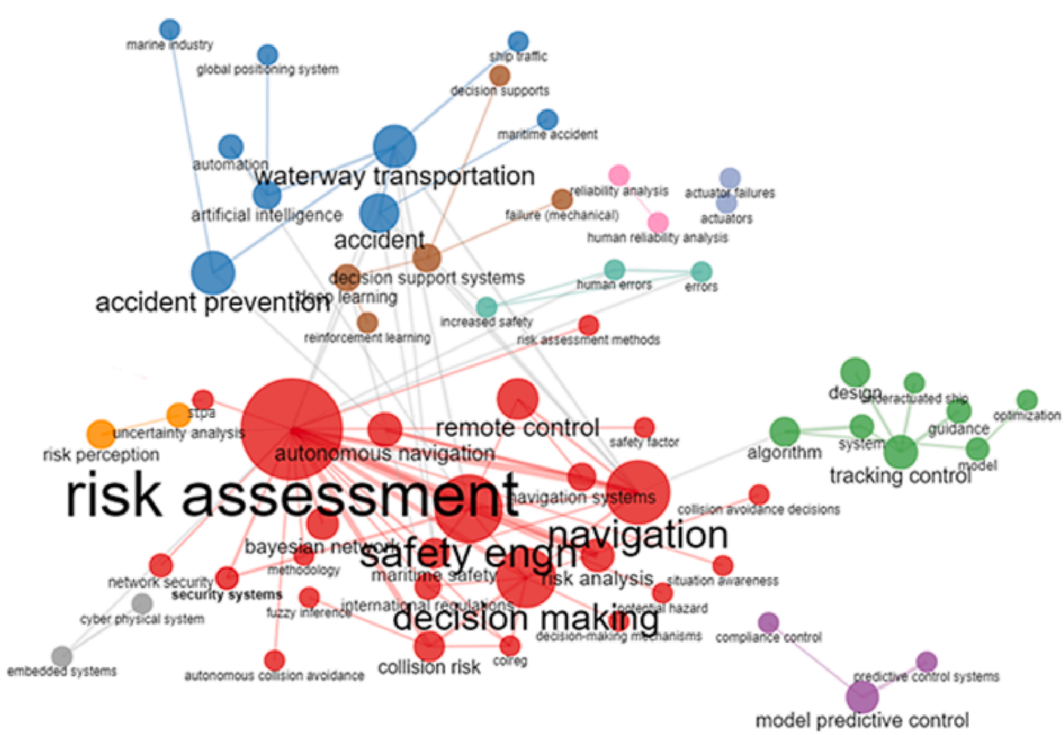

Fig. 12. Terms analysis network.

suggests that a high number of studies related to autonomous ship safety encompass studies that have examined the dynamics of collision risks and formulated algorithms for collision avoidance. Furthermore, the Navigation Systems node is in proximity to the terms "colreg" and "international maritime regulation," which most probably refers to the consideration of rules outlined in the COLREGS convention in the design of navigation systems and algorithms to mitigate collision risks.

Several interrelated small clusters (pink, blue, teal) appear in the thematic network corresponding to the concepts of human reliability analysis, human errors, actuator failures, and reliability analysis. Despite their significance to the field of safety and reliability of autonomous ships, these topics appear to be underrepresented in published research records.

Fig. 12 illustrates that the small grey cluster is closely connected to the risk assessment cluster, primarily via the "network security" node. The grey cluster revolves around the concept of "cyber-physical systems", which is also in proximity to the "security systems" node in the red cluster. These results indicate that network security and communication security are pertinent to the safety of autonomous ships and that cybersecurity is gaining increased attention from researchers in the field of autonomous ship safety. It should be noted that while this theme was not included in the search keywords for this study, the bibliometric analysis has detected cybersecurity in the network depicted in Fig. 12. This suggests that, concerning autonomous ships, security issues are fundamentally linked to safety concerns, and cyber threats may be incorporated into the risk assessment of autonomous vessels. This also supports previous studies that evaluated cyber-attacks as potential risks for autonomous ships (Bolbot et al., 2019; (Glomsrud and Xie, 2019); Guzman et al., 2019; Kavallieratos et al., 2019; Tusher et al., 2022). Additionally, it can be proposed that the safety and cyber security analysis can be further investigated, and more formal methods for safety and security co-analysis can be studied in future research.

The thematic analysis is another important step to study through bibliometric reviews (Aria et al., 2022). This analysis makes the review more comprehensive as it allows for capturing the critical themes in the specific field of research in addition to identifying their trend. Using the keywords of the publications, the thematic analysis in this study is conducted using the thematic map in R, which locates the important themes according to their relevance to the field and their development degree. The results are shown in 13, where the x-axis represents the relevance of the themes to the field of safety and reliability of autonomous ships, and the y-axis represents the development degree of each theme. As depicted in 13, there are four quadrants (main clusters) of themes based on relevance and development degrees.

According to Fig. 13, the themes at the very top right of the map, which are "risk assessment", "navigation", and "collision avoidance", are motor themes for the research topic of safety and reliability of autonomous ships. It means that these research themes are well-developed and relevant to the field of autonomous ship safety and reliability. Being well-developed implies that a relatively high number of research studies have already been conducted covering these themes. Therefore, the research on these themes is usually of substantial impact on the field. The themes of "security systems" and "network security" are located almost in the centre of the map, which explains their relevance

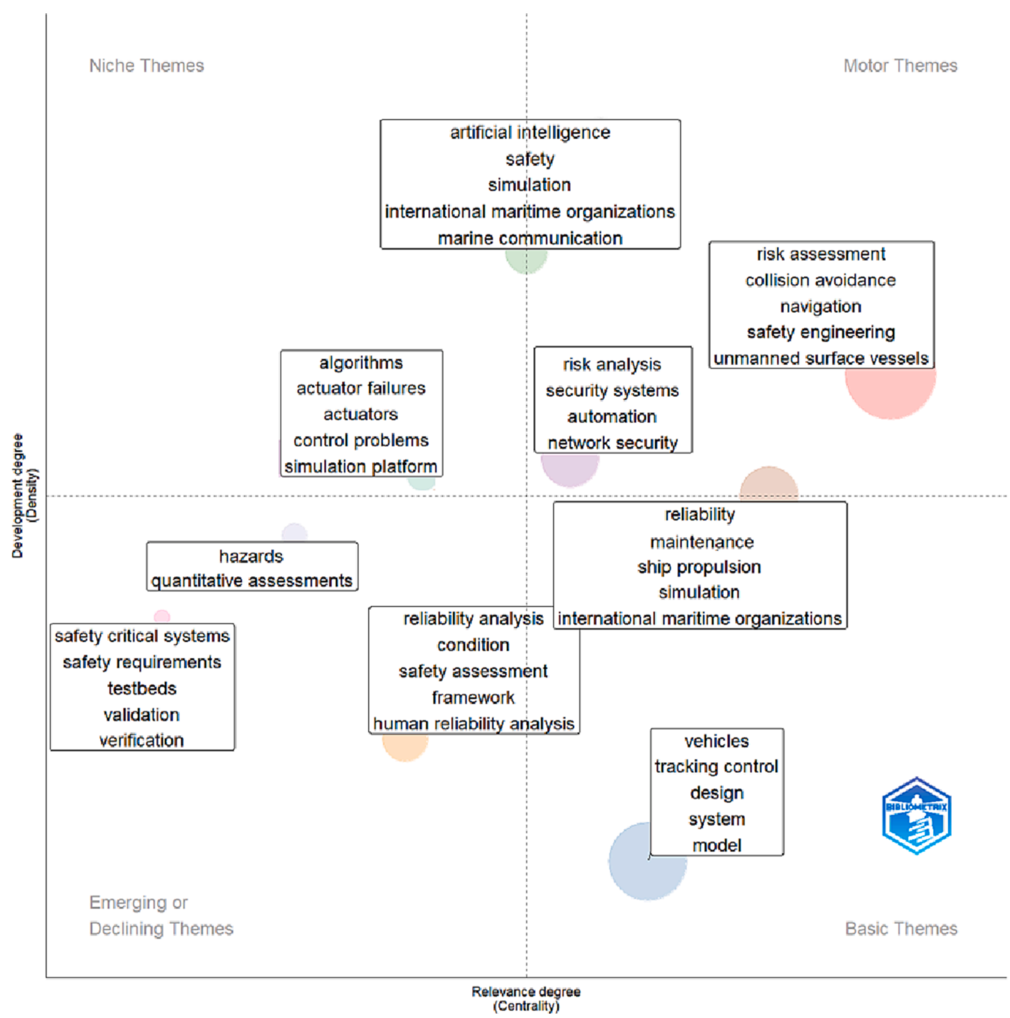

Fig. 13. Thematic map of the discussed topics in the publications.

for the field of autonomous ship safety.

Themes like "simulation" and "artificial intelligence" located in the middle between the niche themes, quadrant and motor themes are relatively well-developed and relevant for the specific research topic on the safety and reliability of autonomous ships. One important quadrant in the themes map is the bottom left quadrant. The corresponding themes are either developed and not relevant for the research topic under focus or relevant, but not developed enough and thus emerging topics. In this respect, the map reveals that "quantitative assessments", "reliability analysis" and "human reliability" are emerging themes in the research on autonomous ship safety and reliability, despite the assumption that these topics should qualify as motor themes. It was recently highlighted that effective reliability assessment models and quantitative tools are needed to tackle the safety challenges of autonomous ships and advance their development (Abaei and Hekkenberg, 2020; BahooToroody et al., 2022a).

Other themes pointed out in Fig. 13 are the themes of "actuator failures", "control problems" and "simulation platforms", which seem to be relevant for autonomous ship safety but are also relatively well-developed themes. The actuator failures and control problems are keywords in the systems theory and the related hazards analysis techniques such as "STPA"(Leveson, 2016), which were captured in Fig. 13 as a hazard analysis method used for autonomous ship risk assessments. This method has also been previously recognized as relevant for autonomous ship safety analysis (Chaal et al., 2020a; Rokseth et al., 2019). The themes of "validation", "verification" and "testbeds" seem to be in the emerging quadrant depicting that are likely to be considered in future research. Finally, the lower right corner of the thematic map provides the basic themes of research in the field of autonomous ship safety and reliability. Examples of these themes are "models", "system", and "design", which are employed in many publications in connection to risk and safety. Overall, these themes are considered highly relevant, but of general and basic use in this field.

Taken all together, the discussed results of this thematic map suggest that some relevant topics for future research in the field of autonomous ship safety and reliability can be related to emerging topics of quantitative risk assessment techniques, verification tests and validation, cybersecurity risk assessment, reliability analysis, human reliability analysis, and also system-theoretic safety analysis methods.

3.3.2. *Top 30 paper deeper content analysis*

In Fig. 14 the distribution of the most popular employed methods in the top 30 papers from Table 2 per different categories is depicted. Fig. 14 total does not sum up to thirty, as several papers have employed multiple methods e.g. (Chang et al., 2021). As can be observed, a relatively high number of influential papers are studies that implemented autonomous ship navigation control. A meaningful interpretation of such a finding is that in the case of autonomous and especially unmanned ships, the control systems can have a high impact on safety.

The navigational risk assessment as a part of the design of autonomous navigation for safety can be considered one of the most popular methods in the most influential articles. The frequent use of System-Theoretic Process Analysis (STPA) is also notable for the identification of hazards in autonomous ships in the top articles. This finding is in line with the conclusions provided by Zhou et al., (2020). The use of Bayesian Networks for risk modelling has also been frequent in the top paper.

These thirty publications are grouped into five main categories and analysed in more detail in the next sections with respect to their content.

3.3.2.1. Navigation risk assessment and control theory. An analysis of the most influential papers revealed an uneven concentration on the various features of MASS with Navigation Risk Assessment being excessively studied in comparison to the other components. The studies on navigational risk assessment can be clustered into two divisions of statistical learning-based navigation risk assessment (Chen et al., 2018; Chun et al., 2021; Gil, 2021; Liu et al., 2017; Zhao et al., 2016), and control based navigation analysis (Chen et al., 2018; Huang et al., 2021; Liu et al., 2017; Zhao et al., 2021). The most significant studies in both clusters were centred around developing collision avoidance systems (Chen et al., 2018; Chun et al., 2021; Gil, 2021; Huang et al., 2021, 2020; Zhao et al., 2016).

In this regard, Gil et al., (2021) improved the concept of Collision Avoidance Dynamic Critical Area (CADCA) to determine the required manoeuvring area for prospective MASS given the dynamic nature of her operations in close-quarters situations. To this end, the critical distance between two objects (Minimum Distance to Collision) was utilized. The deflection of the rudder and ship speed has been identified as the most and least influential factors on the size of the CADCA, respectively. Zhao et al., (2016) integrated the COLREGs guidelines into a real-time collision avoidance model for MASS. Utilizing evidential reasoning is used to determine the potential collision risk posed by the obstacles encountered. The authors put the optimal reciprocal collision avoidance (ORCA) algorithm into practice to address the possible collision avoidance manoeuvre that adheres to COLREGS rules. Huang et al., (2020) proposed a time-dependent collision risk assessment, to facilitate the collision avoidance system being able to produce timely solutions. The model can evaluate the risk of nearing ships as well as the complexity of evading a collision. The authors successfully illustrated that ignoring ship manoeuvrability will lead to underestimation of collision risk. A MASS manoeuvring decision-making framework was formulated by Xue et al., (2019) in order to rank the primary components that influence

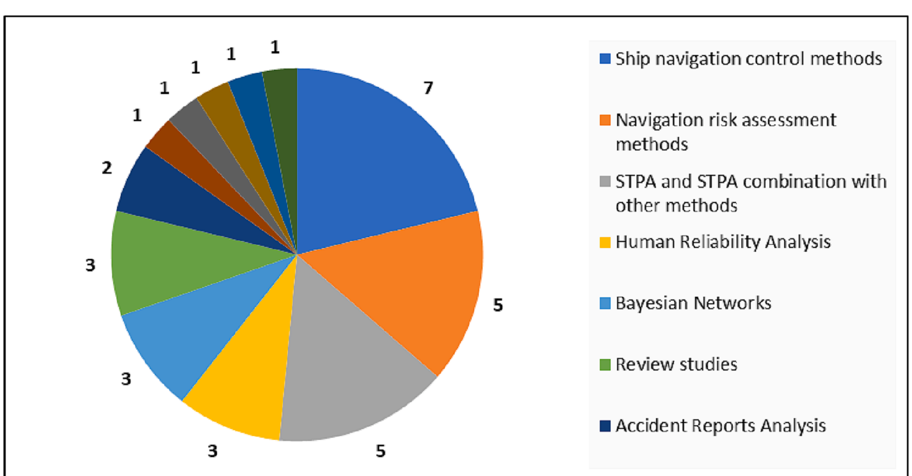

Fig. 14. The allocation of employed methods and study types in the top 30 papers.

ship manoeuvring decisions. This purpose was served by blending grey relational analysis, fuzzy approach, and expert linguistic terms, incorporating multi-source influencing factors, such as the ship's motion and environmental conditions, into the proposed decision-making model.

Control theory-based models aim at forming control schemes and ultimately analysing ship collision avoidance. A number of learning approaches were used in studying this cluster, yet the primary objective was to analyse and regulate navigation risk with the help of control models. The idea of Cooperative Multi-Vessel Systems was brought forward in reference to the vessel train formation problem by Chen et al., (2018) in order to consider not merely cooperative collision prevention, but also the clustering of vessels. By varying two parameters, Huang et al., (2021) investigated alternative control behaviours, including offsets to the guidance course angle of the autopilot and changes to the propulsion command. A ship collision risk analysis was carried out later to determine how each of the alternative control behaviours would affect collision hazards. A simulated prediction has been employed to select the optimal control behaviour selected, given the Convention on the International Regulations for Preventing Collisions at Sea. Qin et al., (2020) and Johansen et al., (2016) studied the saturation problem in developing control models and trajectory-tracking control strategies. Authors considered three principal sources of perturbation for the model: external disturbance, model uncertainties, and input saturation constraints. For verification, numerical simulations were proposed.

Utilizing Deep Reinforcement Learning (DRL), Chun et al., (2021) built a quantitative collision avoidance method to calculate collision risk and then construct a path of evasion. The vessel domain and the closest point of approach were used as the input. Accordingly, the route that adhered to the COLREGs was made based on the rudder angle of the own ship, which was set as the output of the DRL. As a further study in the realm of DRL, Zhao et al., (2021) developed a control model that is intended to be used for MASS path following. The recommended model can self-modify in response to new information. The proposed control model was evaluated by way of simulation. In another similar control-based collision avoidance study, Liu et al., (2017) applied a developed form of line-of-sight guidance algorithm to address control problems of path following within MASS.

A control strategy was designed and optimized by (Maki et al., 2020) for off-line automatic berthing of MASS, with the risk of collision with the berth being taken into account. The primary technique utilized was a covariance matrix adaption evolution strategy, with the control inputs of a propeller and rudder being considered.

3.3.2.2. Review studies. As brought up before, several papers are concentrating on navigation risk assessment and collision avoidance using advanced control systems advanced control and navigation systems. While designing a ship without a crew, more complications come up than simply navigation and control, such as machinery plant, online communication, and cyber-security which all need to be further analysed. This discrepancy is also made evident in two influential review papers Gu et al., 2021) and Thieme et al., (2018), wherein Gu et al., (2021) separated the MASS-associated literature into 10 sections with safety as one of them, and of the 49 reviewed papers, 83% (41) were devoted to collision risks and avoidance. This is while, navigation control is thought of as its own category. Thieme et al., (2018) defined 9 evaluation criteria to assess the usability of developed risk models through 64 published studies for MASS operations. The identified criteria considered different aspects of MASS operation, including:

- software and control algorithm performance,
- human–machine interfaces and ergonomic considerations,
- communication; between vessels and the shore base, and operators among themselves and with other members of the marine community,
- maintenance and reliability of the system with functional redundancy in scope,
- different operational modes and changes in the level of autonomy.

After an in-depth investigation, the authors demonstrate that only ten documents meet six or more of the stipulated criteria, but none of them was applicable to MASS risks analysis.

3.3.2.3. STPA based studies. As already mentioned, the application of STPA to autonomous ships has resulted in some very influential publications. In (Utne et al., 2020), the use of STPA with BBN for the development of supervisory risk control models in autonomous systems was proposed. In the follow-up research studies (Johansen and Utne, 2022; Yang and Utne, 2022), this idea was further enhanced and its practical application in virtual environments was demonstrated. The development of supervisory risk control systems constitutes a generally novel research area in autonomous ships with practical applications not only to autonomous ships but also to conventional ships (Bolbot et al., 2021).

In (Chaal et al., 2020b; Valdez Banda et al., 2019; Wróbel et al., 2018a, 2018b) the sole use of STPA without combining it with other safety analysis methods was observed. In (Wróbel et al., 2018a) the integration into STPA of the uncertainty metrics as suggested by Flage and Aven, (2009) was implemented supporting the prioritization of risks and research in autonomous ships. Valdez Banda et al., (2019) conducted risk management in autonomous ships based on the criteria related to cost of the measures and mitigation approach for the STPA-identified scenarios. In (Wróbel et al., 2018b), slightly different from (Valdez Banda et al., 2019), risk management criteria in STPA were proposed, but for remotely controlled vessels. Chaal et al., (2020) focused on the design issues related to MASS with the support of STPA. All in all, in the influential papers from this category, the effectiveness of STPA was emphasised due to its capability to identify different types of hazards especially those related to the unsafe behavior of the system control models. Additionally, these studies pointed out that STPA is applicable through the early development phases, which is the current situation in MASS. These studies concentrated on enhancing the method for tailored applicability to autonomous ships.

3.3.2.4. Other safety analysis methods-based studies. Bayesian networks, human reliability analysis techniques, and accident analyses constitute some of the most popular methods employed in the area of risk, safety and reliability for top papers in autonomous ships that we have identified. The use of BN is anticipated, as the method can allow easy modelling of rather intricate interactions. At the same time, the use of BBN is always accompanied by the use of other methods in the top papers (Chang et al., 2021; Utne et al., 2020; Zhang et al., 2020). This can be attributed to the fact that whilst the method is good for modelling the interactions, it is not supportive in identifying scenarios and understanding the impact of various failure modes or hazards (ISO, 2019). So, any subsequent use of BBN would be preferably integrated with other methods.

The investigation of human–machine interactions in MASS using advanced and traditional techniques in the top papers (Ramos et al., 2020, 2019; Zhang et al., 2020) is noticed. The criticality of the control and feedback loop between humans and automation makes this topic of high importance. According to Perrow (1999) the implementation of automation frequently causes complexity to increase, thus making accidents more likely. However, the application of probabilistic assessment is complicated in these types of studies due to the lack of credible data for probabilities of human failure (Ramos et al., 2020, 2019). All these studies concentrated on the Remote-Control Centre since the human operator is expected to be present there.

The use of accident investigation reports for autonomous ships as referred, has contributed to the top influence among the considered papers. The investigations carried out by Wróbel et al., (2017) and de

Vos et al., (2021) revealed the domains in which the implementation of MASS will significantly influence safety regarding the types of accidents, vessels, and magnitude. These studies' findings question the widely disseminated claim that the adoption of MASS will eradicate 80% of accidents attributed to human error. Thus, the actual impact of these studies can be even greater than depicted by citations, as they contribute to a paradigm shift. Accident analysis, although tedious in terms of resources has been a powerful technique to uncover critical information about ship safety and has been extended to inland waterways also (Bačkalov et al., 2023).

The use of other safety methods such as FMEA (Chang et al., 2021), Event Sequence Diagrams (Ramos et al., 2020) or novel methods such as 4P4F (Fan et al., 2020) is also notable. The use of FMEA for risk assessment on the ship level contradicts the common practice of applying HAZID as required in class societies (Bureau Veritas, 2019; DNV, 2018) or STPA as done often by the researchers (Zhou et al., 2020). Usually, FMEA is applied on the system level for different machinery components failure identification, however, such an application has been a novel aspect of the work. The use of Event Sequence Diagrams as in (Ramos et al., 2020) is interesting as the method is old and most popular in the nuclear industry (Acosta and Siu, 1993). in line with its popularity in other industries such as nuclear, but not in autonomous shipping has been popular in other industries as it is an old method, especially nuclear. However, applying such an established method to MASS should not be surprising.

3.3.2.5. Other studies. Few studies could not be directly assigned into previous categories. Abaei et al., (2021) focused on enhancing the reliability of propulsion systems in MASS. This is an arising topic, which is very important in the context of unmanned ships. It was noticeable that this is the unique publication in the top 30 papers that contributed to the reliability analysis of machinery systems in MASS.

Goerlandt, (2020) investigated the issues associated with the risk governance and risk acceptance in autonomous ships. It was emphasised that risk acceptance and MASS approval are serious obstacles causing concerns to the decision-making stakeholders. The study proposes that there is a challenge concerning not only checking the safety aspects of MASS according to the absolute realist risk view but also the societal and uncertainty aspects in the risk analyses. Lastly, Neural Networks-based image recognitions presented by Chen et al., (2020) is a topic with significant implications for the safe design of MASS. The research on safe object detection has a high impact as well and was covered by Chang et al., (2021) and Fan et al., (2020).

3.3.3. Autonomous ship challenges and directions for future research based on top papers

Additionally, the analysis of the gaps and recommendations in the top 30 articles indicate that the following topics need to be considered thoroughly to ensure the safety of autonomous ships. These topics are not independent but instead linked to each other.

3.3.3.1. Software error and hardware failures during design and operation:. Cost-effective management of software errors and hardware failures during design and operation is paramount as they have a direct influence on the safety of autonomous ships, especially for unmanned cases, where no crew is available to rectify any problems (Chang et al., 2021; Fan et al., 2020; Gu et al., 2021; Kim et al., 2020; Thieme et al., 2018; Wróbel et al., 2018b, 2018a). Regarding this matter, the greatest identified challenge is to ensure that no failure has been left unaddressed. Such a problem is strongly linked to the completeness of identified hazardous scenarios following up a risk assessment study during the design (Chang et al., 2021; Utne et al., 2020; Wróbel et al., 2018b, 2018a) especially the common cause failures (Fan et al., 2020). As a result, there is a need for better integration between the safety processes and the design processes (Valdez Banda et al., 2019), tailored methods for hazard identification and analysis (Utne et al., 2020), and increased fault tolerance and resilience in the design, especially in accidents such as fire, mechanical breakdowns, or unpredicted situations (Chang et al., 2021; de Vos et al., 2021; Wróbel et al., 2018b, 2018a, 2017).

For ship operations, it is necessary to develop efficient safety management systems for autonomous ships (Aslam et al., 2020; Chaal et al., 2020b; Valdez Banda et al., 2019; Wróbel et al., 2018b, 2018a). Development of online risk estimation and monitoring models (Utne et al., 2020) is an innovative type of system with high potential for further development as already mentioned, with a focus on the integration of the system with others on the ship and its testing (Utne et al., 2020). The maintenance activities will need to be updated and integrated into the safety management systems. Novel systems to support predictive maintenance should also be developed (Abaei et al., 2021). However, obtaining an adequate amount of error/failure data might be a special challenge, that needs to be addressed (Abaei et al., 2021). It is also important to ensure that the responsibilities for safety management are clarified in the context of MASS (Valdez Banda et al., 2019).

3.3.3.2. Autonomous navigation safety. Addressing uncertainty and complexity in navigation of autonomous ships should be prioritized considering the criticality of autonomous navigation as reflected in previous sections (Chang et al., 2021; Chen et al., 2020; Gil, 2021; Gu et al., 2021; Huang and van Gelder, 2020; Johansen et al., 2016; Utne et al., 2020; Wróbel et al., 2017; Xue et al., 2019; Zhao et al., 2016). This includes focusing on factors such as weather and traffic complexity in waterways. The development of reliable image recognition algorithms for small objects is also important to enable adequate situation awareness and safe detection of aids to navigation present in the area (Chen et al., 2020). Autonomous navigation in conditions such as ice, low visibility and strong tides remains a problem yet to be solved (Chang et al., 2021). The verification and validation of the autonomous navigation algorithms is a further challenge to be investigated and regulated (Utne et al., 2020). The COLREGs rules that impact decision making in ships' encounter, such as Rule 72 and Rule 17 should be unified, and uncertainty should be eliminated to enable the development of collision avoidance algorithms with safe and unambiguous behaviour (García Maza and Argüelles, 2022). The technical challenges of navigational interactions between autonomous and conventional ships require attention and more research (Gu et al., 2021). The specification of autonomous collision avoidance test scenarios can be further studied because neglecting vital elements as input for navigation risk analysis would impede the reliable collision avoidance models. Test scenarios should be capable of detecting the overestimation or underestimation of collision risks.

A narrow range of statistical learning approaches has been typically employed for autonomous navigation modelling. Although clustering (Gil, 2021; Huang et al., 2020) and reinforcement learning (Chun et al., 2021; Zhao et al., 2021) have seen extensive use, dimensionality reduction and anomaly detection are areas that necessitate further investigation. The utilization of dimensionality reduction methods can decrease the difficulty of ship movement data and highlight the most essential characteristics, while anomaly detection can detect atypical ship movement behaviors that may signify a probable hazard. Among clustering approaches, K-mean approach has been widely used in segmenting hazardous traffic situations, while more advanced unsupervised machine learning techniques can be further investigated (e.g., Hierarchical Clustering, Density-based Clustering, Gaussian Mixture Models).

3.3.3.3. Regulatory update and technology acceptance. The formulation of new regulations for MASS has been started at the IMO level (IMO, 2021). Yet, this is still ongoing work with several challenges that need to be addressed (Kim et al., 2020). The focus should be on the development of suitable regulations guiding the design and navigation of autonomous ships (Chaal et al., 2020b; Fan et al., 2020; Wróbel et al., 2018b), which is the key to enabling technology in MASS. The current version of the COLREGs rules for example need elaborations and amendments in order to mitigate the inherent uncertainties in their interpretation (Zhou et al., 2020a). In particular, the GOLREGs Rule 5 concerning the "Look-out" needs amendment to allow for a replacement by computer vision (Zhou et al., 2020a).

To support the technologies acceptance, it also necessary to involve research on estimating accurately the safety impact of autonomous ships on the maritime industry (de Vos et al., 2021) and determining the acceptable risk level for MASS (either qualitative or quantitative). This can be achieved by considering the different stakeholders' perspectives and perceptions and the existing approaches to risk acceptance as well as uncertainties (Goerlandt, 2020; Utne et al., 2020). Developing adequate risk acceptance criteria will also support the insurance of MASS (Fan et al., 2020; Ramos et al., 2019; Wróbel et al., 2018b).

3.3.3.4. Human-Machine interactions. Enhancing the human factors' performance in new operational environments such as Remote Control Centers should be deeply investigated (Chang et al., 2021; Fan et al., 2020; Wróbel et al., 2018b, 2018a, 2017). This involves addressing performance-shaping factors such as cognitive aspects, psychological aspects, situation awareness factors, skills, training, and cooperation. Human performance during emergency situations represents a considerable impediment that should be solved with additional research work (Zhang et al., 2020). Hazard identification techniques involving the analysis of human actions should properly incorporate the sequence of actions by the operator during the analysis (Ramos et al., 2020). But such analysis results are directly influenced by the experience of the safety analyst, thus, reducing this subjectivity can be tackled in future research.

3.3.3.5. Safety and cybersecurity. The interactions between safety and cybersecurity in autonomous ships need to be carefully addressed (Aslam et al., 2020; Chang et al., 2021; Kim et al., 2020; Wróbel et al., 2018a). This refers especially to the accidents caused by cyber-attacks through fragile telecommunications channels, such as AIS which can be easily spoofed or tampered with (Aslam et al., 2020). Furthermore, as the vulnerability to cyberattacks is exacerbated by the fact, that ships are interconnected with multiple actors and systems, the development of a new geo-distributed secure network will be strongly needed (Aslam et al., 2020; Gu et al., 2021).

3.3.3.6. Uncertainty in risk assessment. Addressing uncertainty in the risk (Fan et al., 2020; Goerlandt, 2020; Wróbel et al., 2018b) with very limited data (Abaei et al., 2021; Thieme et al., 2018) due to the novelty and ambiguity of the design concept are among the remaining obstacles in the MASS risk assessment. This is intensified by the fact that even conventional ships are designed in limited series, so the relevant failure data is scarce, especially with the rather slow and few available tests (Abaei et al., 2021). Special challenge refers to the uncertainty in navigational risk assessment considering the influence of COLREGs (Huang and van Gelder, 2020; Namgung and Kim, 2021; Xue et al., 2019) and the bias accompanying the use of expert ranking for safety assessment (Fan et al., 2020; Wróbel et al., 2018a). Adopting appropriate and transparent methods to communicate uncertainty should be considered in future research studies (Wróbel et al., 2018a, 2018b).

3.3.3.7. Safety analysis methods enhancement. The adjustment of the safety methods for application to MASS is an important potential topic of the research. For instance, it was mentioned that STPA has been extensively applied to MASS problems (Zhou et al., 2020b) and as also is derived from our bibliometric analysis. However, STPA is not aligned till now with the existing maritime regulatory framework, which needs to be addressed (Wróbel et al., 2017). Also, there has been research on how to allow prioritisation for hazards or mitigation measures in STPA (Valdez Banda et al., 2019; Wróbel et al., 2017) for MASS or how to integrate with BN or other methods to derive quantitative results which can be addressed further as well (Utne et al., 2020). Ground-breaking safety analysis methods for MASS similar to the 4P4F published by Fan et al, (2020) can be also developed. On the other hand, exploring the application of conventional safety methods outside their typical boundaries, such as FMEA which was upgraded with BN in (Chang et al., 2021), can be deliberated on in future research.

3.4. Limitations

Publications not indexed in Scopus or Web of Science were not considered as part of the bibliometric and later thematic analysis. In addition, our criteria did not include any publications in other languages than English. Nevertheless, many leading researchers opt to publish their research in these databases in English, thus making sure that the most distinguished publications are documented here. The scope and findings of this study are centred around academic output and exclude any patents and industrial innovations unless they are documented in scientific publications.

As a part of the thematic analysis, we analysed only the top 30 articles in depth. In this way, the challenges and research directions, which are highlighted in these articles have been captured. The marked impact of these articles implies that these problems and research directions are the ones that the maritime community is considering when engaging in research. Consequently, investing in those challenges or research directives could yield a considerable effect. However, this is not an exhaustive list of safety challenges and potential research directions, as this is not a comprehensive review.

A certain limitation is introduced by the use of specific keywords for the search. We considered those keywords related to MASS linked using AND gate with the keywords related to risk, safety, and reliability such as hazard, failure, and accident. In this way, the search results are more bound to the safety risk, rather than financial and other types of risk. But this was done intentionally to focus on those aspects of MASS rather than the others.

When aggregating the results of our analysis, some of our methodological steps resembled that of the PRISMA method. In comparison with PRISMA though we did not use screening and eligibility assessment steps. After the data collection and merging, we went directly to data analysis. This was intentional, as we wanted to avoid subjectivity in our analysis, which can appear in these steps due to each expert judgement and experience when it comes to each paper's inclusion. Instead, we wanted to follow the results that are provided by the tools we used to enhance the replicability of the results. Also, we filtered the irrelevant subject fields such as chemistry and robotics control from our research. Otherwise, the implementation of analysis and update would be too tedious, considering the number of publications included. This is in line with many other bibliometric reviews which have been published, including Safety Science publications such as van Nunen et al. (2018), Yang et al. (2019), and Merigó et al. (2019).

4. Conclusions

This study evaluates the macro trends in autonomous ship safety and reliability literature between 01/01/2011 and 31/12/2022. The research in the field of autonomous ship safety and reliability gained attention gradually starting in 2011 but has experienced an exponential evolution since 2016. The latest identified trends suggest that the research field is far from saturation and that more research can be effectively carried out. However, the coming years will reveal whether this exponential growth trend will persist. The results and the concise conclusions of this paper will support the government, industry, and academia in identifying the key information about bibliometrics and research trends on the topic of autonomous ship safety and reliability. It will facilitate the establishment of fruitful and impactful future research, maritime policies, and resource allocation. The paper will also help the junior researchers, or researchers newly targeting the field of autonomous ship safety and reliability, to get familiar with the trends and necessary information for an effective introduction to this field of research.

The collection of publications used as the dataset in this bibliometric review contains 417 scientific papers on the safety and reliability of autonomous ships, which are written by 940 authors and published in 242 journals and conference proceedings. By conducting the systematic analysis as described in the methodology, this bibliometric review study provides thought-provoking information about many aspects of the publications:

-The most active journals publishing on autonomous ship safety and reliability in terms of publication number and scientific impact are the journal of Ocean Engineering and the journal of Reliability Engineering and Systems Safety and the journal of Safety Science.

-Of the 417 publications on autonomous ship safety and reliability, only 8.63% are single-authored papers.

−10.55% of the publications are co-authored by researchers from different territories, while the remaining 89.45% are either single-authored or co-authored by researchers from the same country.

-There is a potential for more research collaboration among the authors as the average number of co-authors in multi-authored papers is 3.75 co-authors per paper.

-Only ten institutions publish nearly 80% of the included papers.

-More than 90% of the publications are produced by only three countries, China, Norway, and the USA.

The analyses carried out in this paper have also identified the outstanding contributors to this research field:

-Countries such as Norway, South Korea, Finland, and Poland, which are maritime nations with maritime policies habitually focusing on ship design and/or seafaring, have high scientific production and impact on the field of autonomous ship safety and reliability.

-The journal article entitled “A framework to identify factors influencing navigational risk for Maritime Autonomous Surface Ships”, written by Fan et al., (2020) is the most impactful single publication having 42.50 average citations per year.

-An important number of close collaboration networks have already been established in the field of autonomous ship safety and reliability. The authors Montewka.J, Wrobel.K, Li.Y, Utne.I, Lui.Z, Kujala.P, Van Gelder.P, and Valdez Banda.O have relatively active collaboration in this field of research.

-China is the most productive country, producing 62.83% of the total publications.

-Poland has the highest scientific impact, with an average of 25.50 citations per publication, followed by Norway and the UK.

-Wuhan University of Technology is the most productive institution, having published 19.42% of the total publications.

Some potential gaps were also highlighted regarding the collaboration of the countries and territories in the context of the targeted research field:

-There is less scientific activity in the African continent and Latin America.

-South Korea, the fourth most productive country, seems to have limited international scientific collaboration.

-A number of most industrialised countries, such as Germany, France, Canada, and Italy, have relatively low scientific production on this research topic. These countries may have relevant publications in other languages, prioritized patent-related research, or have the subject of autonomous shipping less urgent in their maritime policies.

-The identified gaps suggest future international collaboration with countries such as South Korea, Germany, France, Italy, South Africa, Morocco, and Brazil.

Besides, this study has also provided insights into the main themes of research on the safety and reliability of autonomous ships. In this respect, the findings provide an understanding of the challenges and considerations involved in ensuring the safe and reliable operation of autonomous ships.

-One of the identified main research themes is “safety engineering and risk assessment for decision making.” This theme underscores the importance of developing robust safety engineering practices and effective risk assessment methodologies to inform decision-making processes in the context of autonomous ships.

-Another significant research theme is “navigation safety and collision avoidance.” As autonomous ships navigate the seas, ensuring their safe interaction with other vessels and avoiding collisions becomes crucial. This research theme contributes to the development of effective technologies and regulations to mitigate navigation risks of autonomous ships.

-The theme of “cybersecurity risk analysis” highlights the importance of addressing cybersecurity concerns in the context of autonomous ships. With increasing reliance on advanced technologies and connectivity, autonomous ships are vulnerable to cyber threats, which can also have consequences on the safety of ship operations.

-Furthermore, the study reveals that methods such as STPA (System-Theoretic Process Analysis) and Bayesian Networks are popular approaches employed in the studies conducted within this research topic. These methods offer systematic frameworks and probabilistic modelling techniques to analyse and assess risks of autonomous ships.

-In terms of future research directions, the research themes of “reliability analysis and quantitative assessments,” “human reliability analysis,” and “system-theoretic safety analysis” hold promise. These areas offer opportunities to delve deeper into the quantitative assessment of reliability, consider human factors and their impact on safety, and apply system-theoretic approaches to analyse and enhance the overall safety and reliability of autonomous ship operation.

Additionally, the investigations of the top 30 articles revealed that:

-Topics related to navigational risk assessment, control theory, STPA, safety analysis and risk governance resulted in high research impact.

-The development of safe collision avoidance systems seems to be at the centre of the research in navigation risk assessment type studies.

-The research applying STPA to MASS has concentrated on improving STPA or combining it with other methods.

-It is preferred to use Bayesian Networks in combination with safety methods for more effective safety analysis in MASS.

-Development of novel methods for MASS can also result in highly impactful publications, yet such cases are few.

-The accident investigation analysis-based studies have challenged some well-established propositions about the safety of MASS.

The investigation of the most impactful publications has also illuminated a number of potential future research directions in MASS safety, risk and reliability. These include:

-Developing either novel or altered traditional methods that are robust for the risk assessment of MASS during their lifecycle.

-Addressing the risks from other ship systems such as machinery plants, not only navigation risk assessment because more complications can come from other systems as well.

-Increasing the availability of MASS-relevant failure/test data and statistics.

-Developing tailored maintenance and safety management systems for MASS.

-Reducing uncertainty during MASS risk assessment and safety assurance and developing methods for uncertainty communication.

-Developing risk acceptance criteria for MASS.

-Addressing the COLREGs rules ambiguities to enable the development of safe collision avoidance algorithms for autonomous ships.

-Developing verification and validation techniques for MASS collision avoidance.

-Addressing the cybersecurity risks with the support of effective methods that take into consideration the distributed network.

-Investigating different machine learning techniques for collision risk modelling such as dimensionality reduction and anomaly detection.

Finally, this bibliometric review has some limitations. As with any other bibliometric analysis, the input dataset is extracted from databases using search keywords, which might cause the inclusion of a few publications that are not 100% under the research topic of interest. One more limitation is that the content themes of the publications were analysed with quantitative tools, which might imply some uncertainties with the results. It should also be mentioned that the analysis was limited to English-language publications, although valuable activities in other languages, such as Korean, Japanese, or Chinese, might exist.

CRediT authorship contribution statement

Meriam Chaal: Conceptualization, Methodology, Software, Investigation, Data Curation, Writing – Original Draft, Writing – Review and Editing. **Xin Ren:** Conceptualization, Methodology, Software, Writing – Review and Editing. **Ahmad BahooToroody:** Investigation, Visualization, Writing – Review and Editing. **Sunil Basnet:** Methodology, Data Curation, Writing – Review and Editing. **Victor Bolbot:** Writing – Original Draft, Writing – Review and Editing. **Osiris A. Valdez Banda:** Writing – Review and Editing, Supervision, Funding Acquisition. **Pieter Van Gelder:** Conceptualization, Writing – Review and Editing, Supervision.

Declaration of Competing Interest

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

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References

Abaei, M., Hekkenberg, R., 2020. A Method to Assess the Reliability of the Machinery on Autonomous Ships, in: 19th Conference on Computer Applications and Information Technology in the Maritime Industries. pp. 11–13.

Abaei, M.M., Hekkenberg, R., BahooToroody, A., 2021. A multinomial process tree for reliability assessment of machinery in autonomous ships. Reliab. Eng. Syst. Saf. 210, 107484 https://doi.org/10.1016/j.ress.2021.107484.

Acosta, C., Siu, N., 1993. Dynamic event trees in accident sequence analysis: application to steam generator tube rupture. Reliab. Eng. Syst. Saf. 41, 135–154. https://doi.org/10.1016/0951-8320(93)90027-V.

Aria, M., Cuccurullo, C., 2017. bibliometrix: an R-tool for comprehensive science mapping analysis. J. Informet. 11, 959–975. https://doi.org/10.1016/j.joi.2017.08.007.

Aria, M., Misuraca, M., Spano, M., 2020. Mapping the evolution of social research and data science on 30 years of social indicators research. Soc. Indic. Res. 149, 803–831. https://doi.org/10.1007/s11205-020-02281-3.

Aria, M., Cuccurullo, C., D'Aniello, L., Misuraca, M., Spano, M., 2022. Thematic analysis as a new culturomic tool: the social media coverage on COVID-19 pandemic in Italy. Sustainability 14, 3643. https://doi.org/10.3390/su14063643.

Aslam, S., Michaelides, M.P., Herodotou, H., 2020. Internet of ships: a survey on architectures, emerging applications, and challenges. IEEE Internet Things J. 7, 9714–9727. https://doi.org/10.1109/JIOT.2020.2993411.

Bačkalov, I., Vidić, M., Rudaković, S., 2023. Lessons learned from accidents on some major European inland waterways. Ocean Eng. 273, 113918 https://doi.org/10.1016/j.oceaneng.2023.113918.

BahooToroody, A., Abaei, M.M., Banda, O.V., Kujala, P., De Carlo, F., Abbassi, R., 2022a. Prognostic health management of repairable ship systems through different autonomy degree; from current condition to fully autonomous ship. Reliab. Eng. Syst. Saf. 221, 108355 https://doi.org/10.1016/j.ress.2022.108355.

BahooToroody, A., Abaei, M.M., Valdez Banda, O., Montewka, J., Kujala, P., 2022b. On reliability assessment of ship machinery system in different autonomy degree. A Bayesian-based approach. Ocean Eng. 254, 111252 https://doi.org/10.1016/j.oceaneng.2022.111252.

Basnet, S., Valdez Banda, O.A., Chaal, M., Hirdaris, S., Kujala, P., 2020. In: Proceedings of the International Seminar on Safety and Security of Autonomous Vessels (ISSAV) and European STAMP Workshop and Conference (ESWC) 2019. Sciendo, pp. 125–139.

Bautista-Bernal, I., Quintana-García, C., Marchante-Lara, M., 2021. Research trends in occupational health and social responsibility: a bibliometric analysis. Saf. Sci. 137, 105167 https://doi.org/10.1016/j.ssci.2021.105167.

Bogusllwski, K., Nasur, J., Li, J., Gil, M., Wrobel, K., Goerlandt, F., 2022. A cross-domain scientometric analysis of situational awareness of autonomous vehicles with focus on the maritime domain. IEEE Access 10, 50047–50061. https://doi.org/10.1109/ACCESS.2022.3174097.

Bolbot, V., Theotokatos, G., Boulougouris, E., Wennersberg, L.A.L., Nordahl, H., Rødseth, Ø.J., Faivre, J., Colella, M.M., 2020. Paving the way toward autonomous shipping development for European Waters – The AUTOSHIP project. Royal Institution of Naval Architects, London.

Bolbot, V., Kulkarni, K., Brunou, P., Banda, O.V., Musharraf, M., 2022. Developments and research directions in maritime cybersecurity: a systematic literature review and bibliometric analysis. Int. J. Crit. Infrastruct. Prot. 39, 100571 https://doi.org/10.1016/j.ijcip.2022.100571.

Chaal, M., Valdez Banda, O.A., Glomsrud, J.A., Basnet, S., Hirdaris, S., Kujala, P., 2020. A framework to model the STPA hierarchical control structure of an autonomous ship. Saf. Sci. 132, 104939 https://doi.org/10.1016/j.ssci.2020.104939.

Bolbot, V., Theotokatos, G., Wennersberg, L.A., Faivre, J., Vassalos, D., Boulougouris, E., Jan Rødseth, Ø., Andersen, P., Pauwelyn, A.-S., Van Coillie, A., 2021. A novel risk assessment process: application to an autonomous inland waterways ship proceedings of the institution of mechanical engineers, part O. J. Risk and Reliability 237 (2), 436–458.

Chaal, M., Bahootoroody, A., Basnet, S., Valdez Banda, O.A., Goerlandt, F., 2022. Towards system-theoretic risk assessment for future ships: a framework for selecting Risk Control Options. Ocean Eng. 259, 111797 https://doi.org/10.1016/j.oceaneng.2022.111797.

Chae, C.-J., Kim, M., Kim, H.-J., 2020. A study on identification of development status of MASS technologies and directions of improvement. Appl. Sci. 10, 4564. https://doi.org/10.3390/app10134564.

Chang, C.-H., Kontovas, C., Yu, Q., Yang, Z., 2021. Risk assessment of the operations of maritime autonomous surface ships. Reliab. Eng. Syst. Saf. 207, 107324 https://doi.org/10.1016/j.ress.2020.107324.

Chen, Z., Chen, D., Zhang, Y., Cheng, X., Zhang, M., Wu, C., 2020. Deep learning for autonomous ship-oriented small ship detection. Saf. Sci. 130, 104812 https://doi.org/10.1016/j.ssci.2020.104812.

Chen, L., Hopman, H., Negenborn, R.R., 2018. Distributed model predictive control for vessel train formations of cooperative multi-vessel systems. Transp. Res. Part C: Emerging Technol. 92, 101–118. https://doi.org/10.1016/j.trc.2018.04.013.

Chun, D.-H., Roh, M.-I., Lee, H.-W., Ha, J., Yu, D., 2021. Deep reinforcement learning-based collision avoidance for an autonomous ship. Ocean Eng. 234, 109216 https://doi.org/10.1016/j.oceaneng.2021.109216.

Dabi, Y., Darrigues, L., Katsahian, S., Azoulay, D., De Antonio, M., Lazzati, A., 2016. Publication trends in bariatric surgery: a bibliometric study. OBES SURG 26, 2691–2699. https://doi.org/10.1007/s11695-016-2160-x.

de Klerk, Y., Manuel, M.E., Kitada, M., 2021. Scenario planning for an autonomous future: a comparative analysis of national preparedness of selected countries. Mar. Policy 127, 104428. https://doi.org/10.1016/j.marpol.2021.104428.

de Vos, J., Hekkenberg, R.G., Valdez Banda, O.A., 2021. The impact of autonomous ships on safety at sea – a statistical analysis. Reliab. Eng. Syst. Saf. 210, 107558 https://doi.org/10.1016/j.ress.2021.107558.

DNV, 2018. Autonomous and remotely operated ships.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., Lim, W.M., 2021. How to conduct a bibliometric analysis: an overview and guidelines. J. Bus. Res. 133, 285–296. https://doi.org/10.1016/j.jbusres.2021.04.070.

Ellefsen, A.L., Æsøy, V., Ushakov, S., Zhang, H., 2019. A Comprehensive survey of prognostics and health management based on deep learning for autonomous ships. IEEE Trans. Reliab. 68, 720–740. https://doi.org/10.1109/TR.2019.2907402.

Fan, C., Wróbel, K., Montewka, J., Gil, M., Wan, C., Zhang, D., 2020. A framework to identify factors influencing navigational risk for Maritime Autonomous Surface Ships. Ocean Eng. 202, 107188 https://doi.org/10.1016/j.oceaneng.2020.107188.

Flage, R., Aven, T., 2009. Expressing and communicating uncertainty in relation to quantitative risk analysis (QRA). Reliability & Risk Analysis: Theory & Application 132.

García Maza, J.A., Argüelles, R.P., 2022. COLREGs and their application in collision avoidance algorithms: a critical analysis. Ocean Eng. 261, 112029 https://doi.org/10.1016/j.oceaneng.2022.112029.

Gil, M., 2021. A concept of critical safety area applicable for an obstacle-avoidance process for manned and autonomous ships. Reliab. Eng. Syst. Saf. 214, 107806 https://doi.org/10.1016/j.ress.2021.107806.

Gil, M., Wróbel, K., Montewka, J., Goerlandt, F., 2020. A bibliometric analysis and systematic review of shipboard Decision Support Systems for accident prevention. Saf. Sci. 128, 104717 https://doi.org/10.1016/j.ssci.2020.104717.

Glomsrud, J.A., Xie, J., 2019. A Structured STPA Safety and Security Co-analysis Framework for Autonomous Ships. Presented at the ESREL 2019.

Goerlandt, F., 2020. Maritime autonomous surface ships from a risk governance perspective: interpretation and implications. Saf. Sci. 128, 104758 https://doi.org/10.1016/j.ssci.2020.104758.

Gou, X., Liu, H., Qiang, Y., Lang, Z., Wang, H., Ye, D., Wang, Z., Wang, H., 2022. In-depth analysis on safety and security research based on system dynamics: a bibliometric mapping approach-based study. Saf. Sci. 147, 105617 https://doi.org/10.1016/j.ssci.2021.105617.

Gu, Y., Goez, J.C., Guajardo, M., Wallace, S.W., 2021. Autonomous vessels: state of the art and potential opportunities in logistics. Intl. Trans. in Op. Res. 28, 1706–1739. https://doi.org/10.1111/itor.12785.

Guzman, N.H.C., Kufoalor, D.K.M., Kozine, I., Lundteigen, M.A., 2019. Combined safety and security risk analysis using the UFoI-E method: A case study of an autonomous surface vessel 8.

Hannaford, E., Maes, P., Van Hassel, E., 2022. Autonomous ships and the collision avoidance regulations: a licensed deck officer survey. WMU J. Marit. Affairs 21, 233–266. https://doi.org/10.1007/s13437-022-00269-z.

Hirsch, J.E., 2005. An index to quantify an individual's scientific research output. Proc. Natl. Acad. Sci. U.S.A. 102, 16569–16572. https://doi.org/10.1073/pnas.0507655102.

Hoem, Å.S., Fjortoft, K., Rødseth, Ø.J., 2019. Addressing the accidental risks of maritime transportation: could autonomous shipping technology improve the statistics? TransNav. 13, 487–494. https://doi.org/10.12716/1001.13.03.01.

Huang, Y., Chen, L., Chen, P., Negenborn, R.R., van Gelder, P.H.A.J.M., 2020. Ship collision avoidance methods: State-of-the-art. Saf. Sci. 121, 451–473. https://doi.org/10.1016/j.ssci.2019.09.018.

Huang, B., Song, S., Zhu, C., Li, J., Zhou, B., 2021. Finite-time distributed formation control for multiple unmanned surface vehicles with input saturation. Ocean Eng. 233, 109158 https://doi.org/10.1016/j.oceaneng.2021.109158.

Huang, Y., van Gelder, P.H.A.J.M., 2020. Collision risk measure for triggering evasive actions of maritime autonomous surface ships. Saf. Sci. 127, 104708 https://doi.org/10.1016/j.ssci.2020.104708.

IMO, 2021. OUTCOME OF THE REGULATORY SCOPING EXERCISE FOR THE USE OF MARITIME AUTONOMOUS SURFACE SHIPS (MASS).

ISO, 2019. IEC 31010:2019 [WWW Document]. ISO. URL https://www.iso.org/standard/72140.html (accessed 3.8.23).

Johansen, T.A., Perez, T., Cristofaro, A., 2016. Ship collision avoidance and COLREGS compliance using simulation-based control behavior selection with predictive hazard assessment. IEEE Trans. Intell. Transport. Syst. 17, 3407–3422. https://doi.org/10.1109/TITS.2016.2551780.

Johansen, T., Utne, I.B., 2020. In: Risk Analysis of Autonomous Ships, in. Research Publishing Services, pp. 131–138. https://doi.org/10.3850/978-981-14-8593-0_5190-cd.

Johansen, T., Utne, I.B., 2022. Supervisory risk control of autonomous surface ships. Ocean Eng. 251, 111045 https://doi.org/10.1016/j.oceaneng.2022.111045.

Kavallieratos, G., Katsikas, S., Gkioulos, V., 2019. Cyber-Attacks Against the Autonomous Ship, in: Katsikas, S.K., Cuppens, F., Cuppens, N., Lambrinoudakis, C., Antón, A., Gritzalis, S., Mylopoulos, J., Kalloniatis, C. (Eds.), Computer Security, Lecture Notes in Computer Science. Springer International Publishing, Cham, pp. 20–36. https://doi.org/10.1007/978-3-030-12786-2_2.

Kim, M., Joung, T.-H., Jeong, B., Park, H.-S., 2020. Autonomous shipping and its impact on regulations, technologies, and industries. J. Int. Maritime Safety, Environ. Affairs, and Shipping 4, 17–25. https://doi.org/10.1080/25725084.2020.1779427.

Kongsberg, 2017. Autonomous ship project, key facts about YARA Birkeland [WWW Document]. URL https://www.kongsberg.com/maritime/support/themes/autonomous-ship-project-key-facts-about-yara-birkeland/ (accessed 3.1.23).

Krusling, J., 2022. Research Guides: Country Research: Emerging Markets [WWW Document]. URL https://ggu.libguides.com/c.php?g=106866&p=693916 (accessed 9.3.22).

Li, J., Goerlandt, F., Reniers, G., 2021. An overview of scientometric mapping for the safety science community: methods, tools, and framework. Saf. Sci. 134, 105093 https://doi.org/10.1016/j.ssci.2020.105093.

Liu, T., Dong, Z., Du, H., Song, L., Mao, Y., 2017. Path following control of the underactuated USV based on the improved line-of-sight guidance algorithm. Polish Maritime Res. 24, 3–11. https://doi.org/10.1515/pomr-2017-0001.

Liu, X., Zhan, F.B., Hong, S., Niu, B., Liu, Y., 2012. A bibliometric study of earthquake research: 1900–2010. Scientometrics 92, 747–765. https://doi.org/10.1007/s11192-011-0599-z.

Luo, F., Li, R.Y.M., Crabbe, M.J.C., Pu, R., 2022. Economic development and construction safety research: a bibliometrics approach. Saf. Sci. 145, 105519 https://doi.org/10.1016/j.ssci.2021.105519.

Madsen, A.N., Aarset, M.V., Alsos, O.A., 2022. Safe and efficient maneuvering of a Maritime Autonomous Surface Ship (MASS) during encounters at sea: a novel approach. Maritime Transp. Res. 3, 100077 https://doi.org/10.1016/j.martra.2022.100077.

Maki, A., Sakamoto, N., Akimoto, Y., Nishikawa, H., Umeda, N., 2020. Application of optimal control theory based on the evolution strategy (CMA-ES) to automatic berthing. J. Mar. Sci. Technol. 25, 221–233. https://doi.org/10.1007/s00773-019-00642-3.

Merigó, J.M., Miranda, J., Modak, N.M., Boustras, G., de la Sotta, C., 2019. Forty years of safety science: a bibliometric overview. Saf. Sci. 115, 66–88. https://doi.org/10.1016/j.ssci.2019.01.029.

Montewka, J., Wróbel, K., Heikkila, E., Valdez-Banda, O., Goerlandt, F., Haugen, S., 2018. Challenges, solution proposals and research directions in safety and risk assessment of autonomous shipping. Los Angeles 12.

Mørkrid, O.E., Bellingmo, P.R., Wille, E., 2023. Feasibility Study for an Unmanned Deep Sea Bulk Ship and Short Sea Container Ship.

Munim, Z.H., Haralambides, H., 2022. Advances in maritime autonomous surface ships (MASS) in merchant shipping. Marit. Econ. Logist. 24, 181–188. https://doi.org/10.1057/s41278-022-00232-y.

Namgung, H., Kim, J.-S., 2021. Collision risk inference system for maritime autonomous surface ships using COLREGs rules compliant collision avoidance. IEEE Access 9, 7823–7835. https://doi.org/10.1109/ACCESS.2021.3049238.

Negenborn, R.R., Goerlandt, F., Johansen, T.A., Slaets, P., Valdez Banda, O.A., Vanelslander, T., Ventikos, N.P., 2023. Autonomous ships are on the horizon: here's what we need to know. Nature 615, 30–33. https://doi.org/10.1038/d41586-023-00557-5.

Oceanautonomy, 2020. ReVolt: Student-driven innovation alongside DNV GL - Ocean Autonomy Cluster [WWW Document]. URL https://oceanautonomy.no/en-us/oacnews/student-innovation-alongside-dnv-gl (accessed 3.1.23).

Öztürk, Ü., Akdağ, M., Ayabakan, T., 2022. A review of path planning algorithms in maritime autonomous surface ships: navigation safety perspective. Ocean Eng. 251, 111010 https://doi.org/10.1016/j.oceaneng.2022.111010.

Price, D.J.S., 1963. Little Sci. Columbia University Press, New York, Big Sci - Foreword.

Qin, H., Li, C., Sun, Y., Wang, N., 2020. Adaptive trajectory tracking algorithm of unmanned surface vessel based on anti-windup compensator with full-state constraints. Ocean Eng. 200, 106906 https://doi.org/10.1016/j.oceaneng.2019.106906.

Ramos, M.A., Utne, I.B., Mosleh, A., 2019. Collision avoidance on maritime autonomous surface ships: operators' tasks and human failure events. Saf. Sci. 116, 33–44. https://doi.org/10.1016/j.ssci.2019.02.038.

Ramos, M.A., Thieme, C.A., Utne, I.B., Mosleh, A., 2020. Human-system concurrent task analysis for maritime autonomous surface ship operation and safety. Reliab. Eng. Syst. Saf. 195, 106697 https://doi.org/10.1016/j.ress.2019.106697.

Razmjooei, D., Alimohammadlou, M., Ranaei Kordshouli, H.-A., Askarifar, K., 2023. Industry 4.0 research in the maritime industry: a bibliometric analysis. WMU J. Marit Affairs. https://doi.org/10.1007/s13437-022-00298-8.

Rødseth, Ø.J., Burmeister, H.-C., 2012. Developments toward the unmanned ship.

Rolls Royce, 2016. Remote and autonomous ships the next steps.

Smith, D.R., 2007. Historical development of the journal impact factor and its relevance for occupational health. Ind. Health 45, 730–742. https://doi.org/10.2486/indhealth.45.730.

Størkersen, K.V., 2021. Safety management in remotely controlled vessel operations. Mar. Policy 130, 104349. https://doi.org/10.1016/j.marpol.2020.104349.

Tavakoli, S., Khojasteh, D., Haghani, M., Hirdaris, S., 2023. A review on the progress and research directions of ocean engineering. Ocean Eng. 272, 113617 https://doi.org/10.1016/j.oceaneng.2023.113617.

Thieme, C.A., Utne, I.B., Haugen, S., 2018. Assessing ship risk model applicability to Marine Autonomous Surface Ships. Ocean Eng. 165, 140–154. https://doi.org/10.1016/j.oceaneng.2018.07.040.

Torben, T.R., Smogeli, Ø., Glomsrud, J.A., Utne, I.B., Sørensen, A.J., 2023. Towards contract-based verification for autonomous vessels. Ocean Eng. 270, 113685 https://doi.org/10.1016/j.oceaneng.2023.113685.

Tusher, H.M., Munim, Z.H., Notteboom, T.E., Kim, T.-E., Nazir, S., 2022. Cyber security risk assessment in autonomous shipping. Marit. Econ. Logist. 24, 208–227. https://doi.org/10.1057/s41278-022-00214-0.

Umeokafor, N., Umar, T., Evangelinos, K., 2022. Bibliometric and scientometric analysis-based review of construction safety and health research in developing countries from 1990 to 2021. Saf. Sci. 156, 105897 https://doi.org/10.1016/j.ssci.2022.105897.

Utne, I.B., Rokseth, B., Sørensen, A.J., Vinnem, J.E., 2020. Towards supervisory risk control of autonomous ships. Reliab. Eng. Syst. Saf. 196, 106757 https://doi.org/10.1016/j.ress.2019.106757.

Vagale, A., Oucheikh, R., Bye, R.T., Osen, O.L., Fossen, T.I., 2021. Path planning and collision avoidance for autonomous surface vehicles I: a review. J. Mar. Sci. Technol. 26, 1292–1306. https://doi.org/10.1007/s00773-020-00787-6.

Valdez Banda, O.A., Kannos, S., Goerlandt, F., van Gelder, P.H.A.J.M., Bergström, M., Kujala, P., 2019. A systemic hazard analysis and management process for the concept design phase of an autonomous vessel. Reliab. Eng. Syst. Saf. 191, 106584 https://doi.org/10.1016/j.ress.2019.106584.

van Eck, N.J., Waltman, L., 2014. In: Measuring Scholarly Impact. Springer International Publishing, Cham, pp. 285–320.

van Nunen, K., Li, J., Reniers, G., Ponnet, K., 2018. Bibliometric analysis of safety culture research. Saf. Sci. 108, 248–258. https://doi.org/10.1016/j.ssci.2017.08.011.

Bureau Veritas, 2019. Guidelines for Autonomous Shipping.

Wang, B., Pan, S.-Y., Ke, R.-Y., Wang, K., Wei, Y.-M., 2014. An overview of climate change vulnerability: a bibliometric analysis based on Web of Science database. Nat. Hazards 74, 1649–1666. https://doi.org/10.1007/s11069-014-1260-y.

World Bank, 2022. The world bank in China [WWW Document]. World Bank. URL https://www.worldbank.org/en/country/china/overview (accessed 9.3.22).

Wróbel, K., Gil, M., Krata, P., Olszewski, K., Montewka, J., 2021. On the use of leading safety indicators in maritime and their feasibility for Maritime Autonomous Surface Ships. Proceedings of the Insti. Mechan. Eng. Part O: J. Risk and Reliability 237 (2), 314–331.

Wróbel, K., Montewka, J., Kujala, P., 2017. Towards the assessment of potential impact of unmanned vessels on maritime transportation safety. Reliab. Eng. Syst. Saf. 165, 155–169. https://doi.org/10.1016/j.ress.2017.03.029.

Wróbel, K., Montewka, J., Kujala, P., 2018a. System-theoretic approach to safety of remotely-controlled merchant vessel. Ocean Eng. 152, 334–345. https://doi.org/10.1016/j.oceaneng.2018.01.020.

Wróbel, K., Montewka, J., Kujala, P., 2018b. Towards the development of a system-theoretic model for safety assessment of autonomous merchant vessels. Reliab. Eng. Syst. Saf. 178, 209–224. https://doi.org/10.1016/j.ress.2018.05.019.

Xue, J., Van Gelder, P.H.A.J.M., Reniers, G., Papadimitriou, E., Wu, C., 2019. Multi-attribute decision-making method for prioritizing maritime traffic safety influencing factors of autonomous ships' maneuvering decisions using grey and fuzzy theories. Saf. Sci. 120, 323–340. https://doi.org/10.1016/j.ssci.2019.07.019.

Yang, L., Chen, Z., Liu, T., Gong, Z., Yu, Y., Wang, J., 2013. Global trends of solid waste research from 1997 to 2011 by using bibliometric analysis. Scientometrics 96, 133–146. https://doi.org/10.1007/s11192-012-0911-6.

Yang, Y., Reniers, G., Chen, G., Goerlandt, F., 2019. A bibliometric review of laboratory safety in universities. Saf. Sci. 120, 14–24. https://doi.org/10.1016/j.ssci.2019.06.022.

Yang, R., Utne, I.B., 2022. Towards an online risk model for autonomous marine systems (AMS). Ocean Eng. 251, 111100 https://doi.org/10.1016/j.oceaneng.2022.111100.

Zhang, X., Wang, C., Jiang, L., An, L., Yang, R., 2021. Collision-avoidance navigation systems for Maritime Autonomous Surface Ships: a state of the art survey. Ocean Eng. 235, 109380 https://doi.org/10.1016/j.oceaneng.2021.109380.

Zhang, M., Zhang, D., Yao, H., Zhang, K., 2020. A probabilistic model of human error assessment for autonomous cargo ships focusing on human–autonomy collaboration. Saf. Sci. 130, 104838 https://doi.org/10.1016/j.ssci.2020.104838.

Zhao, Y., Li, W., Shi, P., 2016. A real-time collision avoidance learning system for Unmanned Surface Vessels. Neurocomputing 182, 255–266. https://doi.org/10.1016/j.neucom.2015.12.028.

Zhao, Y., Ma, Y., Hu, S., 2021. USV formation and path-following control via deep reinforcement learning with random braking. IEEE Trans. Neural Netw. Learn. Syst. 32, 5468–5478. https://doi.org/10.1109/TNNLS.2021.3068762.

Zheng, T., Wang, J., Wang, Q., Nie, C., Shi, Z., Wang, X., Gao, Z., 2016. A bibliometric analysis of micro/nano-bubble related research: current trends, present application, and future prospects. Scientometrics 109, 53–71. https://doi.org/10.1007/s11192-016-2004-4.

Zhou, X.-Y., Huang, J.-J., Wang, F.-W., Wu, Z.-L., Liu, Z.-J., 2020a. A study of the application barriers to the use of autonomous ships posed by the good seamanship requirement of COLREGs. The J. Navigation 73, 710–725. https://doi.org/10.1017/S0373463319000924.

Zhou, X.-Y., Liu, Z.-J., Wang, F.-W., Wu, Z.-L., Cui, R.-D., 2020b. Towards applicability evaluation of hazard analysis methods for autonomous ships. Ocean Eng. 214, 107773 https://doi.org/10.1016/j.oceaneng.2020.107773.