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Review Article

Human factor in maritime accidents and related analyzing methods: A bibliometric review

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Article information	Abstract
Received: December 23, 2025 Revision: April 26, 2026 Accepted: May 18, 2026	Although there has been significant progress in technology, the human factor remains a key contributor to marine accidents. To shed light on the academic perspective regarding the marine accident-human factor pairing, this study aims to clarify and present intellectual structure via bibliometric analysis. Furthermore, a detailed investigation was implemented using the studies from the last 5 years to better understand emerging trends for the human factor in marine accidents. The results reveal that China and Türkiye are the most productive countries in this field and that institutions and authors from these countries are at the forefront. Especially in recent years, it has been observed that the 'autonomous ship' phenomenon has attracted great attention and has become one of the trending topics. In addition to bibliometric analysis, methodological trends were identified by analyzing relevant studies from the last five years. The findings indicate that statistical methods, Bayesian networks, fuzzy logic, SLIM, and HFACS are the most commonly employed methodologies. It is also found that there is a significant trend towards adopting hybrid approaches that integrate different methods to provide more comprehensive and reliable assessments. By combining bibliometric and systematic content analyses, this study clarifies the intellectual structure of the field and highlights current methodological trends.
Keywords Bibliometric analysis; Human factor; Human reliability; Maritime accident	

1. Introduction

Maritime transportation is characterized by its advantages of low cost and low environmental impact and is crucial for the global economy (Huang et al., 2023). A large proportion of global trade in terms of both value and volume is carried out by maritime transportation (Ferrari et al., 2023). However, shipping operations of such importance have various complexity and safety risks at the same time (Han et al., 2023; Wang et al., 2025). Despite advancements such as improved ship design, regulations, technological advancements, automation, and safety measures, maritime accidents which attract attention occur (Zhang et al., 2022) with devastating results. It should be mentioned herein

that, despite the reduced number of accidents in maritime transportation, the increase in shipping vessel size over time increases the magnitude of the destructive effect (Dominguez-Péry et al., 2021). The human factor is the primary reason for these accidents that can be prevented via improvements in this field.

International Maritime Organization (IMO) Resolution A.884(21) specifically defines ‘human factor’ as acts or omissions, intentional or otherwise, that may adversely affect the functioning of a system or the performance of a task, which directly corresponds to accident causation (IMO, 1999). Conceptually, the “human factor” is a broader concept that encompasses individual, task, organizational, environmental, and systemic conditions affecting human performance. In contrast, “human error” refers to the specific incorrect actions or omissions that may occur under the influence of these conditions. Both terms are included in this study because the existing literature on maritime accidents often classifies studies related to the human element by using one of these concepts or both together.

The literature consistently shows that human factors play a major role in maritime accidents (Fan et al., 2020). 60 - 96 % of total marine accidents (Han et al., 2023; Hong, 2014)) are caused by human factors. Various factors such as poorly written procedures, extreme weather, stress, and work overload are influential in the occurrence of skill-based errors, decision errors, or perceptual errors during shipping operations, particularly in communication, maintenance, etc. (Islam et al., 2020; Zhang et al., 2022). Efforts to find root causes and implement corrective actions are becoming increasingly important (Hasanspahić et al., 2021).

Identifying the critical role of human factor in accidents becomes more crucial in the face of technological innovation and changing global conditions (Mišković et al., 2018; Cinar et al., 2025). In the literature, different analysis methods and approaches have been applied to understand the human factor in marine accidents. Among these are the Human Factors Analysis and Classification System (HFACS) (Ma et al., 2025) which systematically examines human error; Human Reliability Analysis (HRA) methods such as SLIM (Erdem & Akyuz, 2021), CREAM (Lee et al., 2024), and HEART (Navas de Maya & Kurt, 2022) that assess the probability of human error; risk analysis methods such as Fault Tree Analysis (FTA) (Kim et al., 2024) and Failure Mode and Effects Analysis (FMEA) (Ceylan et al., 2022) that aim to identify potential hazards and root causes; Bayesian networks (Nizar et al., 2024), that model complex relationships, and fuzzy logic (Zong et al., 2024), that manages uncertainties. The main objective of these studies is to understand the role of the human factor in marine accidents and to minimize human-related accidents. In addition to these studies, the bibliometric analysis method is widely used to deeply analyze academic studies focusing on specific topics in the maritime field (Huang et al., 2023; Dragović et al., 2024; Ay et al., 2024; Bolbot et al., 2022; Razmjooei et al., 2023; Li et al., 2023). Bibliometric analyses are a useful way to shed light on scientific networks, evaluate the impact of research, identify research trends, and support decision making.

This research comprehensively analyses articles on human factors causing maritime accidents. In the first part of the study, bibliometric analysis was carried out to reveal the productivity of journals, countries, and institutions; to discover the co-occurrence of keywords and collaborations between countries and authors; to evaluate the impacts of journals, authors, and papers, and to explore trend topics and used keywords. The Web of Science database was considered a proper source for this analysis due to its selectivity and reliability. The articles identified in the Web of Science database were filtered by Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, and 300 articles related to the research topic were analyzed by bibliometric analysis. In the second part of the study, systematic content analysis was conducted for 171 articles published in the last 5 years (starting from the beginning of 2020, until the end of 2024). Thus, a comprehensive

evaluation of the research on the role of human factors in maritime accidents is presented by using both bibliometric analysis and systematic content analysis together in the study.

This study provides a comprehensive evaluation of research on the role of the human factor in maritime accidents, considering both a broad historical perspective and the most recent methodological trends. While the bibliometric analysis reveals the overall intellectual structure of the research field, the systematic content analysis highlights trending methodologies and research tendencies, particularly in human factor-oriented approaches to maritime accidents. This dual, integrated perspective not only identifies the current state and knowledge gaps in methodological approaches but also goes beyond a general literature overview by offering a more specific roadmap for future research.

The article is structured as follows: Section 1 is “Introduction” and demonstrates a literature review. Section 2 provides information on materials and methods. Section 3 presents the results of the bibliometric analysis. Section 4 discusses the trends in research methods. Section 5 presents the results of the research and provides suggestions for future research.

2. Methodology

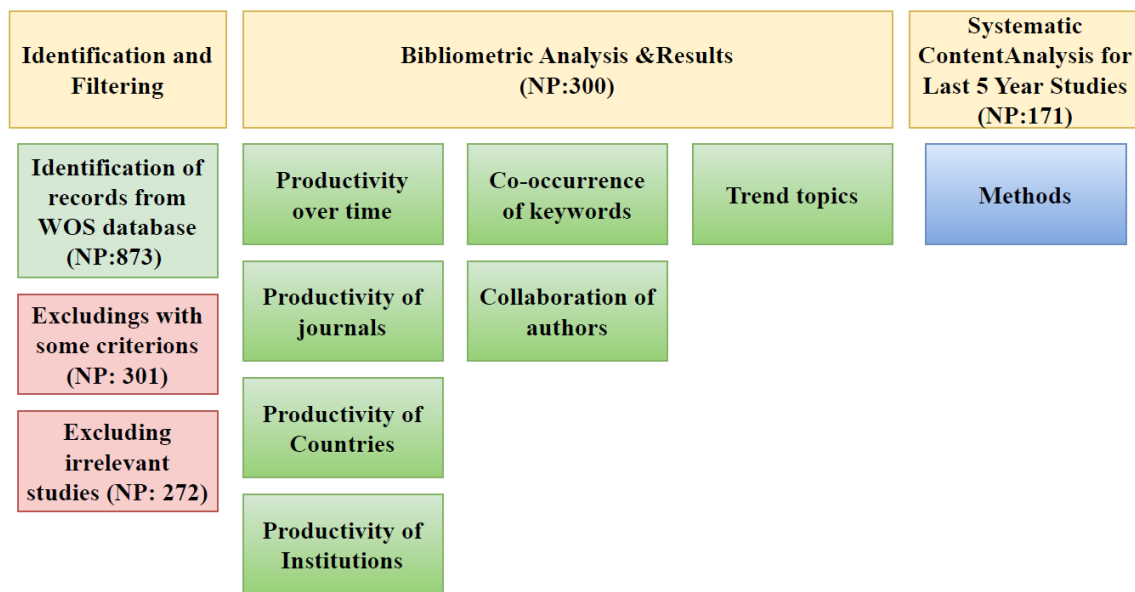
In this section, the methods, software, terminology, and definitions utilized are introduced. In this study, bibliometric analyses were conducted using VOSviewer (‘VOSviewer’, 2026) and Biblioshiny (‘Biblioshiny’, 2026). R is an open source programming language, whereas Rstudio is an integrated development environment (Büyükkidik, 2022). In the study, R version 4.5.0 and Biblioshiny 5.0 were used. Bibliometrix is a package to carry out bibliometric analysis. It is written in the R language and its set of powerful tools enables quantitative research (Aria & Cuccurullo, 2017). Biblioshiny is a web-based interface for Bibliometrix package (Büyükkidik, 2022). It combines the functionality of Bibliometrix package and ease of use of web applications (Arici & Pelit, 2021). The user-friendly Biblioshiny plugin enables exploring and visualizing in real-time (Ay et al., 2024). Compared to other software in this field, Bibliometrix focuses on statistical completeness of the results in addition to data visualization (Derviş, 2019).

Another utilized software is VOSviewer. Network maps can be created, visualized and explored via VOSviewer software (Başhan & Çetinkaya, 2022). It can obtain words from texts via data mining techniques, and it can carry out statistical calculations (Başhan & Ust, 2022). Despite the advantages and disadvantages of the software, it should be noted here that, while using the software, the possibility of bias should be considered. Different names used in manuscripts due to marital changes (van Nunen et al., 2018) and different character existence in author names may create this bias. The stages of this study and used software are demonstrated in **Figure 1**.



Figure 1 Carried out processes and used software in the study.

Each stage and obtained results are demonstrated in **Figure 2**.



*NP: Number of papers

Figure 2 Main stages and obtained results of the study.

Records were identified using a keyword search in the Web of Science database. The Web of Science Core Collection covers 8 indexes, including Science Citation Index Expanded and Emerging Sources Citation Index ('Web of Science Coverage Details', 2026). Despite the broader coverage of other databases (e.g., Scopus) (Alsharif & Baharun, 2020), the Web of Science was chosen for the study because of its selectivity, maturity, and academic credibility (Kaya & Başhan, 2025). This can create bias and can be thought as a limitation of the study. There are different options in the "Advanced search" section, and "Topic" in the "Advanced search" section refers to "title, abstract, keywords plus and author keywords". In this study, "Topic" search was performed using the following Boolean query: ("maritime" OR "marine" OR "vessel*" OR "ship*") AND ("accident*" OR "grounding*" OR "collision*") AND ("human factor*" OR "human error*" OR "human reliability" OR "HRA"). A total of 873 papers were retrieved. Extracting was carried out according to the specified criteria above. Proceeding papers, review papers, and book chapters were excluded, and English-language papers were selected. As a result, a total of 572 papers have been obtained. All the papers were categorized in SCI-E, ESCI, or SSCI indexes.

Among 572 papers, 300 relevant papers were extracted and used in bibliometric analysis. Using bibliometric tools, productivity of authors, countries, institutions in this field, collaborations between countries and authors, and impact of authors, papers, and sources were revealed. In addition to these, most used keywords, keyword occurrences, and trend topics were uncovered. In the latest step, papers published in the last 5 years were refined (from 300 to 171) and systematic content analysis was used. A total of 171 papers were reviewed and examined. They were categorized based on the methods used.

3. Results

In this section, obtained results are illustrated.

3.1 Productivity results

This section informs the reader of productivity results in the field. Publication counts with time, productive institutions, countries, and journals are introduced.

3.1.1 Productivity over time

300 documents were detected in 87 journals, between the 1991 - 2024 time span. All the documents analyzed in this study are article types. In addition to this, 689 author records, 845 authors' keywords, and 8,697 references were observed. Whereas 24 papers of 300 papers are single-authored, an average of 3.64 co-authors per document were detected (average of 300 papers). Internationality between authors was observed as 25 %. This demonstrates that there is an intellectual exchange among researchers from different countries working together to solve the issue. The annual growth rate of publication numbers in the field is found to be 4.16 %. Moreover, average citations per paper are 30.88.

In **Figure 3**, trends in the count of publications is demonstrated. According to the results, there were some studies until 2005 but, after 2005, a steady increase has been observed in published documents. This increment shows us the growing interest in this field.

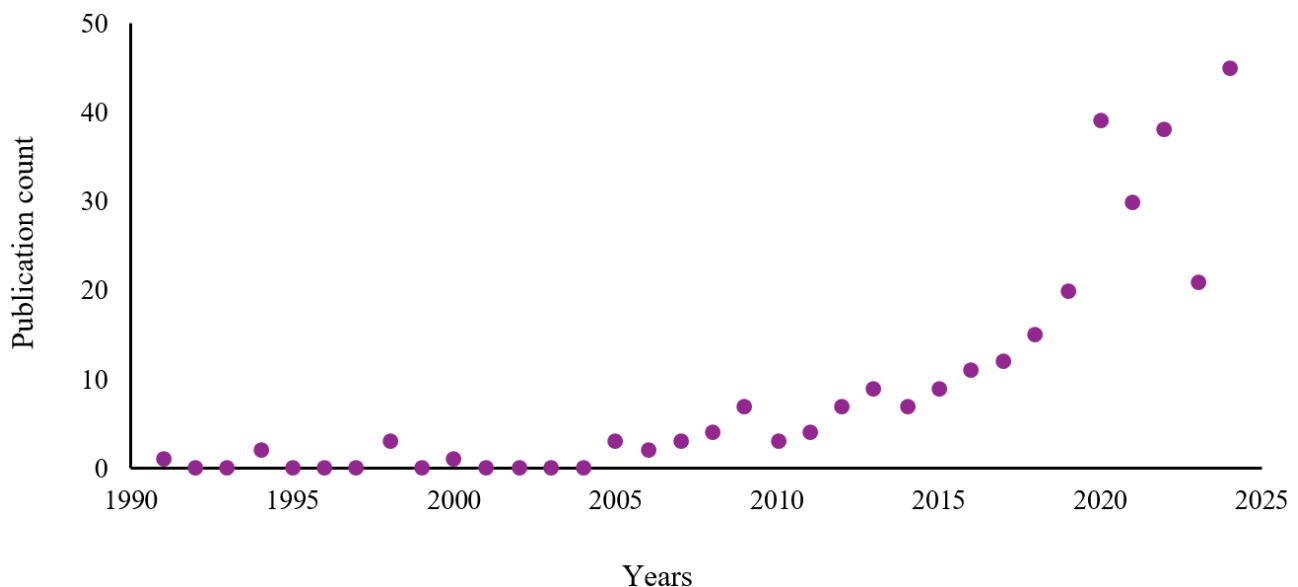


Figure 3 Published paper count per year, between 1991.01.01 - 2024.12.31.

3.1.2 Productivity of institutions

Productive institutional information in the field is important for researchers to find and create new collaborations. **Figure 4** represents the most relevant affiliation names with their counts. Affiliation counts can be found in the Web of Science search. Count is determined according to observing all affiliation names in the article and, if affiliation names are obtained at least 1 time in the article, the count is evaluated as 1. If an author has several affiliations, all affiliations are counted. Results indicate that a total of 228 institution names are detected in this field. Whereas 941 total affiliation records are observed, a total of 163 records belong to 2 or fewer records per institution (88 institution names are recorded just 1 time, and 75 institution names are counted just 2 times). The most observed affiliations in the papers are Istanbul Technical University, with 73 counts, Dalian Maritime University, with 61 counts, Wuhan University of Technology, with 46 counts, Liverpool John Moores University, with 39 counts, Shanghai Maritime University, with 34 counts, Norwegian University of Science and Technology, with 27 counts, University of Strathclyde, with 22 counts, Memorial University of Newfoundland, with 17 counts, Recep Tayyip Erdogan University, with 17 counts, and Karadeniz Technical University, with 16 counts. The top 5 institutions have more than 26 % of the total record count.

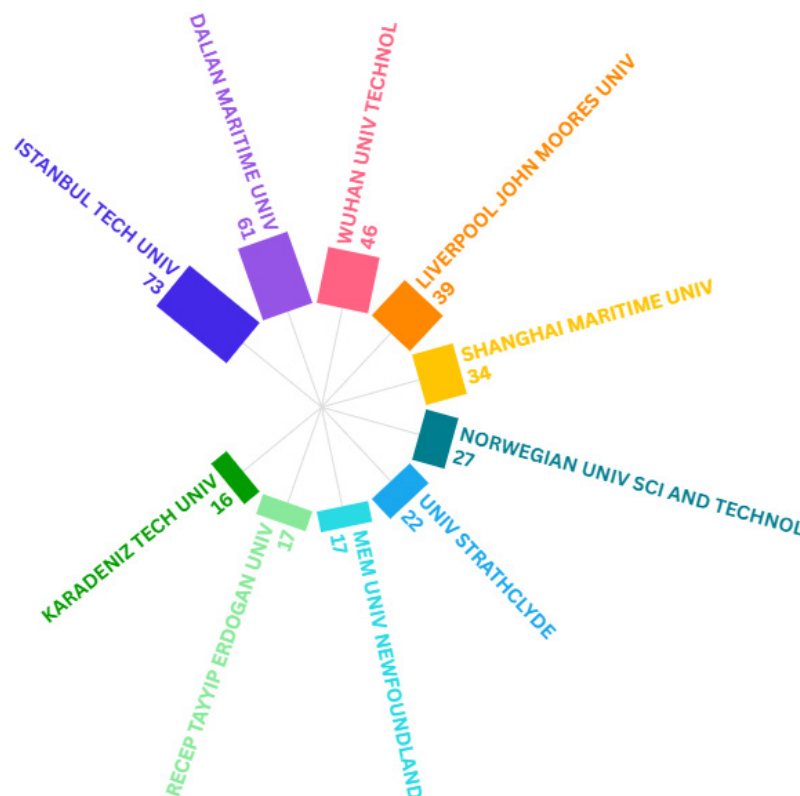


Figure 4 The most relevant affiliations.

3.1.3 Productivity of countries

Countries' interest in the topic is useful to understand the perspectives. In **Figure 5**, a world map is used with scientific production of countries illustrated by color intensity. Darker colors represent increased country name (where the authors' affiliated universities reside) frequency observed in the manuscripts. 39 countries' records are observed. Results show that China dominates the field and has the most contributions with 243 records. Additionally, Türkiye, with 147 records, the United Kingdom, with 86 records, and Norway, with 54 records, are other countries that contribute to this field. China's and Türkiye's contributions are significant; China's share is 26 %, and China's and Türkiye's together are 42 %. In addition to this, European countries' efforts are consistent and significant, as observed on the map. The remaining rankings after China, Türkiye, the United Kingdom, and Norway can be listed as the United States and Croatia, with 35 publications, South Korea and Ukraine, with 31 publications, Poland, with 24 publications, Canada, with 22 publications, Japan, with 21 publications, etc.

3.1.4 Productivity of journals

Total publication count of journals is an important parameter. However, journals' productivity can change with time. Priorities of the journals may diverge and aims and scopes may be modified. For this reason, journal productivity in this field is submitted in **Figure 6** for the top 5 journals (according to the highest h index or the biggest total publication number). It should be noted that results are supplied for publication count per year, instead of cumulative publication count, to see results more transparently. Results show that some of the journals published articles in the last years, and some of them have an increasing or decreasing trend. For example, the productivity of the Journal of Marine Science and Engineering started in 2019 and continues until today. Productivity of Reliability Engineering & System Safety has gained momentum in the last years. Moreover, the productivity of Ocean Engineering is increasing steadily. Safety Science and Transnav-International Journal on Marine Navigation and Safety of Sea Transportation have changed activity over time.

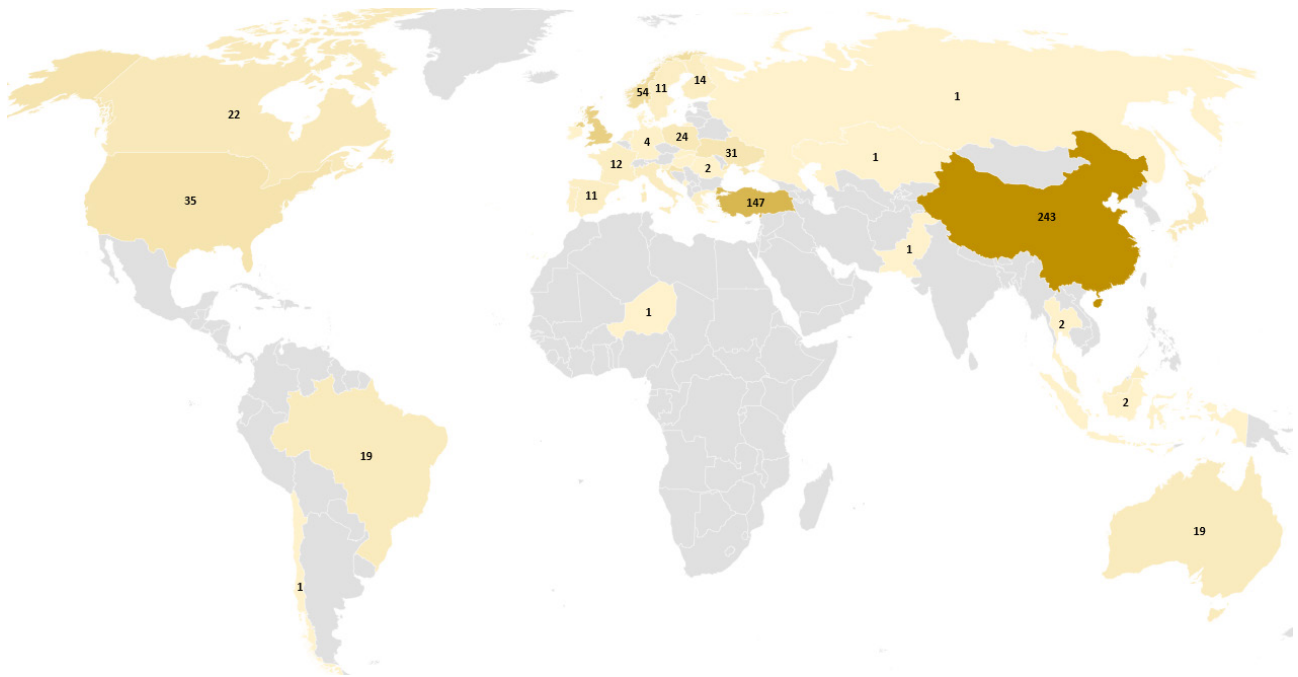


Figure 5 Most productive countries.

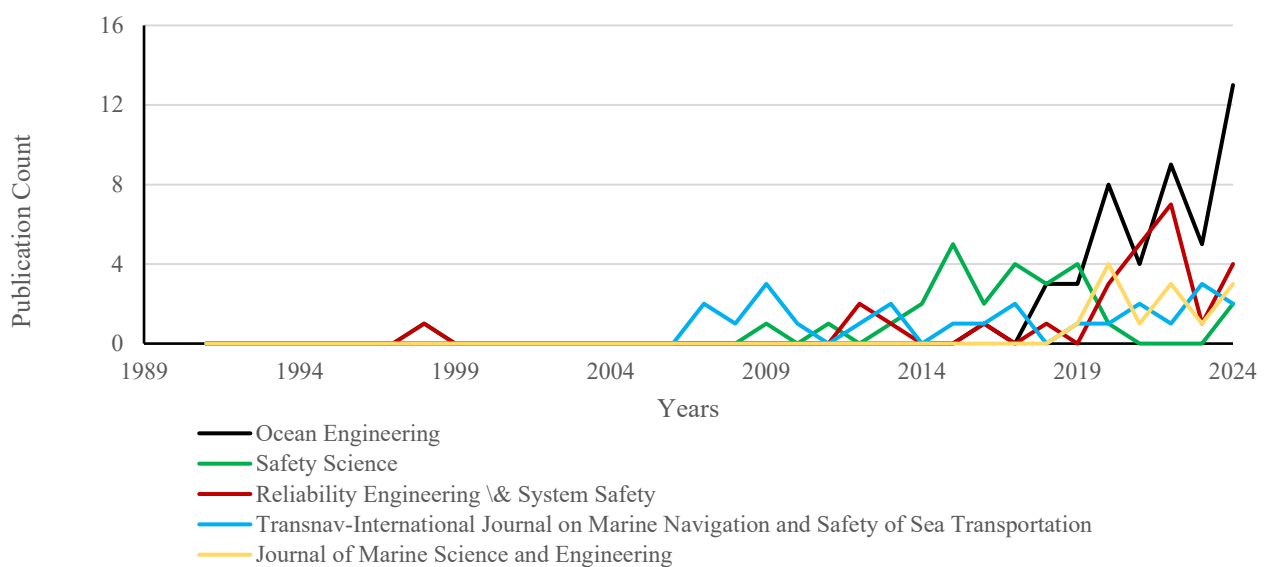


Figure 6 Journals' productivity over time.

3.2 Co-occurrence and collaboration results

In this section, co-occurrences of keywords, collaboration between authors, impact of papers, and trend topics in the field are explained. This analysis summarizes the situation in the field, helping to identify gaps in the literature and pointing to potentials for future studies.

3.2.1 Co-occurrence of keywords

Used keywords in the articles are clustered and their co-occurrence network is demonstrated in **Figure 7**. Minimum 2 occurrences of keywords are selected and a total of 153 keywords are clustered in 15 clusters. "Human factors" as placed in cluster 2, is most occurring keyword, and has biggest link strength. The most occurring keywords are "human factors", at 48 times, "human error", at 46 times, "maritime safety", at 43 times, "human factor", at 30 times, "hfacs", at 26 times,

“maritime accidents”, at 23 times, “bayesian network”, at 17 times, “human reliability”, at 16 times, “human reliability analysis”, at 14 times, and “safety”, at 13 times. Besides these, the relationship between methods and topics should be referred to. For instance, the “maritime autonomous surface” keyword is in the same cluster with “hfacs”. “Fault tree analysis” and “Fuzzy bayesian network” keywords exist with the “tanker” keyword in the same cluster. Whereas “maritime pilotage” is located near “sensitivity analysis”, “d-s evidence theory”, “heart” is located near “ship pms” and “maintenance operations”. “Hfacs-pv” is grouped with “arctic shipping” and “bayesian network”. Last of all, “autonomous shipping” is located in the same group as “data mining”, “interval type 2 fuzzy sets”, “ISM Code”, “goal-directed task analysis”, etc.

Figure 7 Co-occurrence network map of author keywords.

Collaboration patterns between authors may be revealed by co-authorship analysis (Passas, 2024). Co-authorship network of authors is illustrated in **Figure 8**. The minimum published paper count of an author was selected as “1”. Moreover, connected items were selected, and unconnected units were eliminated. For this reason, the remainder of the 215 authors are illustrated in **Figure 8**. There are a total of 19 clusters with 215 author names. Clusters are mentioned with different colors. It should be remembered that, whereas node size depicts the paper number, and lines refer to the network, line thickness refers to repeating the relation. Upon ranking, Emre Akyüz is the first author, with the most publications and, also, with the most link strength.

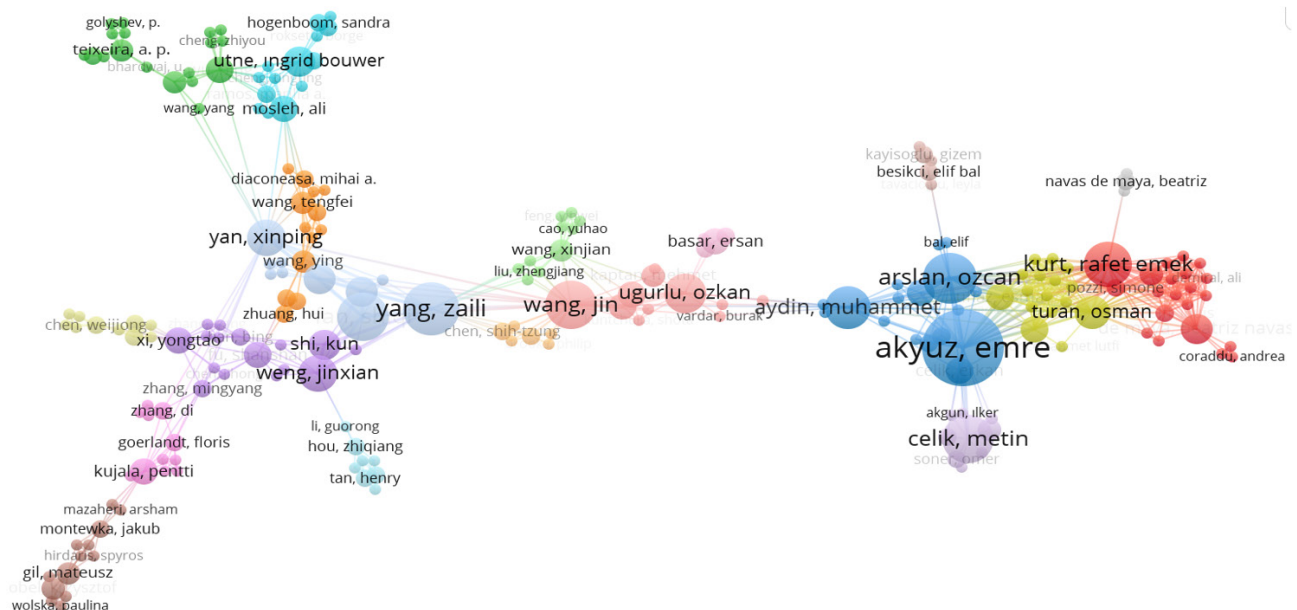


Figure 8 Collaboration network map of authors.

3.3 Trend topics

This study aims to shed light on the future through evaluating trends with time. With the changing time, and with changing priorities, trends have been diverging. For this reason, **Figure 9** illustrates change in trend topics in time. For analysis, authors' keywords were used, minimum word frequency and number of words per year were chosen as “3”, and last of all, timespan was chosen as between 1991 - 2025. Results start from 2006, since the steady study number starts with 2006, as mentioned, and the selection of words per year is 3. According to trends, oldest trends are observed as “accident causation”, “organizational factors”, “ISM Code”, etc. In the intermediate time interval, “decision-making”, “risk assessment”, “fatigue”, “collision”, and “human error” related terms (“human factor”, “human reliability”) are observed as periodic trends. During the last years, significant changes have been observed. Latest trends are obtained as “bayesian network”, “navigation safety”, “SLIM”, “autonomous ships”, “collision accidents”, “evidential reasoning”. In addition to traditional human factor studies, there is a growing focus on the human factor in the context of autonomous ships. Moreover, Bayesian network is among the most currently utilized method topics in recent times.

4. Trends in human factor research on maritime accidents: Insights from the last 5 years (2020 - 2024)

In this section, a systematic content analysis was conducted on 171 articles retrieved from the Web of Science that focus on human factors in marine accidents. Excel-based systematic content analysis was employed to classify, categorize, and statistically evaluate the bibliometric data. The articles were organized in Excel and grouped according to the frequency of methodological approaches used. This approach identifies emerging trends toward human factors in marine accidents and reveals the methodological distribution in the literature. As a result of this systematic analysis, the methods employed across the studies were examined in detail.

4.1 Methods used in the articles

In this section, the research methods applied in the articles written on the research topic between 2020 and 2024 were identified. Manuscript contents were analyzed to determine the methods used in 171 articles. In order to determine the methods, the methodology sections of the articles were analyzed in detail. A statistical summary of the methods is provided in **Table 1**.

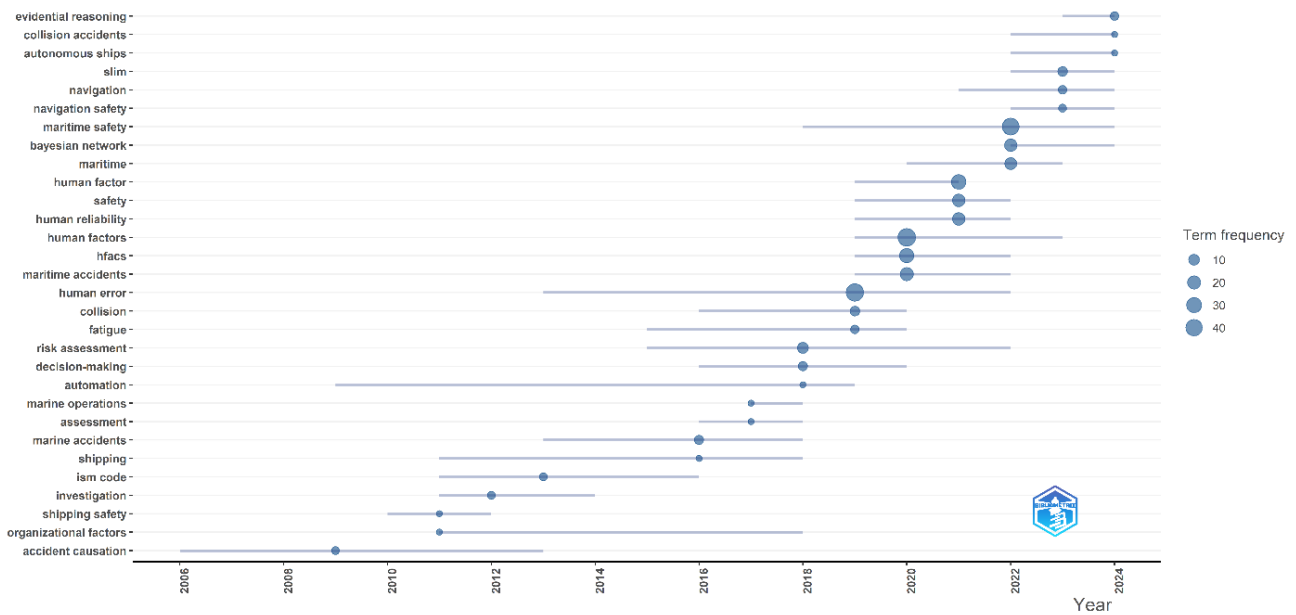


Figure 9 Trend topics in marine accident fields.

Table 1 Number of articles and percentages of used methods in the literature.

Methods used in Articles	No. of Articles	Percentage
Statistical Analysis	30	11.03
BN (Bayesian Network)	29	10.66
Fuzzy Logic	25	9.19
HFACS (Human Factors Analysis and Classification System)	18	6.62
FTA (Fault Tree Analysis)	12	4.41
SLIM (Success Likelihood Index Method)	11	4.04
Machine Learning	10	3.68
CREAM (Cognitive Reliability and Error Analysis Method)	9	3.31
HEART (Human Error Assessment and Reduction Technique)	8	2.94
AHP (Analytic Hierarchy Process)	7	2.57
HFACS-MA (HFACS-Maritime Accidents)	6	2.21
HFACS-PV (HFACS for Passenger Vessel collisions)	5	1.84
DS (Dempster-Shafer) Theory	5	1.84
Artificial Neural Network	5	1.84
Mathematical Modeling	5	1.84
DBN (Dynamic Bayesian Network)	4	1.47
IT2FS (interval type-2 fuzzy sets)	4	1.47
ER (Evidential Reasoning)	4	1.47
IDAC (Information Decision Action in a Crew) Model	4	1.47
FCM (Fuzzy Cognitive Maps)	3	1.10
FMEA (Failure Mode and Effects Analysis)	3	1.10
FRAM (Functional Resonance Analysis Method)	3	1.10
TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)	3	1.10
SOHRA (Shipboard Operation Human Reliability Analysis)	3	1.10
Grounded Theory	3	1.10
Complex Network Theory	3	1.10

Table 1 (continued) Number of articles and percentages of used methods in the literature.

Methods used in Articles	No. of Articles	Percentage
Group Theory	3	1.10
GRA (Gray relational analysis)	2	0.74
ETA (Event Tree Analysis)	2	0.74
Bow-Tie	2	0.74
STAMP (Systems-Theoretic Accident Model and Processes)	2	0.74
TECHR (Technique for Early Consideration of Human Reliability)	2	0.74
H-SIA (Human-System Interaction in Autonomy)	2	0.74
GAP Analysis	2	0.74
Graph Theory	2	0.74
AcciMap (Accident Map)	2	0.74
CBSI (Correlation Based Signal Improvement) method	2	0.74
HFACS-MMO (HFACS for Marine Engineering Operations)	1	0.37
RBBN (Rule-based Bayesian Network)	1	0.37
DDBN (Data-Driven Bayesian Network)	1	0.37
TAN Bayes (Tree Augmented Naive Bayes)	1	0.37
ARBN (Association Rule Bayesian Networks)	1	0.37
Bayesian SEM (Bayesian structural equation modeling)	1	0.37
(Bayesian Spatial Multinomial Logistic Model)	1	0.37
Cloud theory	1	0.37
Fine Kinney	1	0.37
ANP (Analytical Network Process)	1	0.37
DEMATEL (Decision-making Trial and Evaluation Laboratory)	1	0.37
SPAR-H (Standardised Plant Analysis Risk-Human Reliability Analysis)	1	0.37
TRACER (Technique for the Retrospective and Predictive Analysis of Cognitive Errors)	1	0.37
MAART (Maritime Accident Analysis and Reduction Technique)	1	0.37
MOHRA (Maritime Operation Human Reliability Analysis)	1	0.37
IDA (Information Decision Action) Model	1	0.37
DDET (Discrete Dynamic Event Tree)	1	0.37
Data Mining	1	0.37
Logistic Regression	1	0.37
COA (Center of Area)	1	0.37
SHIELD (Safety Human Incident and Error Learning Database)	1	0.37
Ishikawa Diagram	1	0.37
Delphi Method	1	0.37
SAGAT (Situation Awareness Global Assessment Technique)	1	0.37
ADDIE (analysis, design, development, implementation, evaluation) instructional design model	1	0.37
Virtual Reality	1	0.37
Text Mining	1	0.37

The statistical results presented in **Table 1** show that the statistical analysis methods, Bayesian network, fuzzy logic, SLIM, and HFACS are the most frequently used methods in the literature, respectively. The table also indicates the use of new methods derived from these core techniques,

demonstrating a trend where their identified shortcomings are addressed and refined. In particular, hybrid approaches were developed by integrating different methods in order to provide a more systematic and comprehensive examination of the studies. It is seen that human reliability analysis methods, risk analysis methods, and multi-criteria decision-making methods are used effectively in the studies. In the following sub-section, classifications are made by considering the interrelationships of the methods used.

4.1.1 Bayesian network-based studies

The structure of the Bayesian network model, which is widely used in modeling probability-based cause-effect relationships, is based on Bayesian theory (Weber, Medina-Oliva, Simon, & Lung, 2012). Bayesian Network (BN) is often integrated with different methods in studies on the human factor to model probabilistic inference and uncertainty. It is often preferred to handle complex relationships and uncertainties in these studies. The fundamental reason BN is preferred stems from its ability to model the complex and multi-causal nature of human factors in maritime accidents, enabling it to effectively handle probabilistic relationships between crew actions, system failures, and operational conditions.

Bayesian Network-based approaches have been extensively adopted in maritime human factor research to analyze accident scenarios, operational processes, and simulation data, owing to their capability to represent complex causal structures and uncertainties in maritime systems. In addition, several derivative models developed based on Bayesian principles are also employed in similar studies, such as RBBN (Rule-Based Bayesian Network), DBN (Dynamic Bayesian Network), DDBN (Data-Driven Bayesian Network), TAN Bayes (Tree Augmented Naive Bayes), ARBN (Association Rule Bayesian Networks), Bayesian SEM (Bayesian Structural Equation Modeling), and BSMNL (Bayesian Spatial Multinomial Logistic Model).

However, BN-based approaches alone have limited capability in explicitly representing cognitive processes and organizational influences underlying human error. Overall, the flexibility of BN makes it a core component for developing hybrid approaches, enabling researchers to integrate human reliability (HRA) and risk models to provide more robust and comprehensive assessments of human factors in complex maritime systems, thereby mitigating the limitations of single methods.

4.1.2 Uncertainty-based studies

Uncertainty-based methods include fuzzy logic, IT2FS (interval type-2 fuzzy sets), FCM (Fuzzy Cognitive Map), DS (Dempster-Shafer) Theory ER (Evidential Reasoning), Cloud Theory, and GRA (Gray relational analysis). The fact that information in maritime operations is qualitative, imprecise, or uncertain has made uncertainty management an important research area (Zong et al., 2024; Zhang et al., 2024). These methods are used to enhance the consistency of studies, minimize the impact of lack of data, and reduce subjectivity and uncertainty due to reasons such as expert judgment (Ahn et al., 2022). In the context of human reliability assessment, these methods are vital for quantifying subjective human inputs, such as assessing seafarers' workload (Ma et al., 2024) or evaluating human-machine interface operational errors for MASS (Liu et al., 2022).

Fuzzy logic-based approaches dominate uncertainty-driven maritime human factor research, offering flexible tools for modeling imprecise expert judgments in accident and operational risk analyses. Extensions such as IT2FS enhance uncertainty representation, whereas Fuzzy Cognitive Maps enable the analysis of causal interdependencies among human, technical, and environmental elements in maritime accident scenarios.

Beyond fuzzy-based approaches, evidence-based uncertainty methods, such as Dempster-Shafer theory and Evidential Reasoning, have been increasingly applied to human reliability and operational risk assessments in maritime systems, particularly where incomplete or conflicting expert information is present. In addition, cloud theory and Gray Relational Analysis (GRA) have been

employed to support uncertainty modeling and factor prioritization in complex maritime operations and accident analyses.

Consequently, uncertainty-based studies reveal a critical methodological progression in human factor research. They allow for robust human error quantification when objective data is scarce, bridging the gap between qualitative human performance assessment and quantitative risk analysis, which is essential for comprehensive maritime safety evaluations.

4.1.3 HRA-based studies

Human reliability analysis (HRA) is a systematic approach used to identify, measure, and reduce errors by analyzing the human factor involved in an operational process (Hou et al., 2021). In maritime studies, HRA is primarily valued because it translates task-related human performance into quantifiable outputs and allows human contribution to be explicitly incorporated into safety assessments. HRA methods provide quantification of the probability of human errors (HEP), which is critical for risk modeling in maritime systems. In recent years, studies on human factor analysis in the maritime industry have gained increasing importance, and various HRA methods have been applied in these studies.

According to the statistical data in **Table 1**, the most frequently used HRA methods are SLIM, CREAM, and HEART, and these methods are widely preferred in analyzing different maritime operations. This pattern indicates a methodological preference for approaches that can structure expert judgement (SLIM), represent context-dependent performance variability through performance-shaping factors (CREAM), and provide task-oriented error quantification with Error Producing Conditions (EPCs) (HEART), which aligns well with the data-scarce and operationally diverse maritime domain. In addition, TECHR (Technique for Early Consideration of Human Reliability), SPAR-H (Standardized Plant Analysis Risk-Human Reliability Analysis) and TRACER (Technique for the Retrospective and Predictive Analysis of Cognitive Errors) are other important HRA methods. Notably, these methods differ in emphasis: while some are stronger in prospective task-based estimation, others are more suitable for retrospective analysis of cognitive error mechanisms, which explains their selective adoption depending on the accident type and data availability.

Moreover, Shipboard Operation Human Reliability Analysis (SOHRA), Marine Maintenance and Operations Human Reliability Analysis (MOHRA), and Maritime Accident Analysis and Reduction Techniques (MAART) are maritime operations-specific methods derived by modifying the EPC (error-producing conditions), an important parameter of the HEART method, and through some minor computational changes. The development of maritime-specific HRA models (SOHRA, MOHRA, and MAART) reflects the need to recalibrate EPCs to the constraints of shipboard operations, thereby improving the realism and sensitivity of HEP estimates for high-stakes tasks (e.g., engine maintenance, enclosed space entry, or emergency response). However, as with many HRA approaches, a key limitation is the reliance on expert judgement and the challenge of capturing organizational and cultural influences directly; therefore, recent studies often integrate HRA outputs with complementary frameworks to obtain more comprehensive representations of human factors in maritime accidents.

4.1.4 HFACS-based studies

HFACS is a human error analysis method based on Reason's Swiss Cheese model (Maternová et al., 2023). Within the framework of HFACS, the human element consists of four layers that affect each other: unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences (Ma et al., 2025). This method does not only focus on unsafe acts that cause accidents, but also analyses the root causes behind these problems that contribute to human error in maritime accidents. (Ma et al., 2024). HFACS's robust structure allows for the analysis of the systematic and

organizational root causes of maritime accidents, rather than attributing failure solely to individual errors of operational personnel. This multi-layered perspective is particularly valuable in maritime accident analysis, where human error is often shaped by supervisory practices, procedural deficiencies, and organizational culture rather than isolated frontline actions. Due to its flexible structure, it enables quantitative analyses by integrating with different methods such as Bayesian network, grounded theory, logistic regression, DEMATEL, AHP and similar methods. Such integrations allow HFACS classifications to be linked with probabilistic estimation, causal modeling, or decision-support mechanisms.

In order to better address the risks and human factors specific to the maritime sector, different HFACS-based models specific to maritime activities have been developed for the points where the HFACS method is considered insufficient in the evaluation of maritime operations. HFACS-PV (HFACS for Passenger Vessel Collisions), HFACS-MA (HFACS-Maritime Accidents) and HFACS-MMO (HFACS for Marine Engineering Operations) are the methods developed specifically for the maritime sector. HFACS-MA is a maritime adaptation based on IMO guidelines. HFACS-PV differs from the basic model by considering environmental factors at a separate level as a complementary element in accident causation. HFACS-MMO is a model developed for marine engineering and machinery operations. The development of maritime-specific HFACS derivatives reveals the inadequacy of general models and highlights the critical role of unique contextual factors, such as environmental conditions and specific operations, in shaping human error in high-risk maritime environments.

4.1.5 Risk analysis methods

Risk analysis is the process of identifying potential hazards and analyzing the probability of occurrence and effects of these hazards during any maritime system, process or operation (Çinar et al., 2021). In maritime accident research related to human factors research conducted between 2020 and 2024, commonly applied risk analysis methods include Fault Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), Event Tree Analysis (ETA), Bow-Tie analysis, the Fine-Kinney method, Systems-Theoretic Accident Model and Processes (STAMP), and the Functional Resonance Analysis Method (FRAM).

Among these, FTA has been identified as the most preferred risk analysis method in human factors studies for maritime accidents. This method is widely used in root cause analysis of maritime accidents and analyzes causal relationships between sub-events. Similarly, FMEA identifies potential failure modes in the maritime system and analyzes the possible effects of these failures. Traditional linear risk analysis methods like FTA and FMEA are essential in maritime human factors research, primarily because they provide the quantitative structure (causal pathways or failure sequences) necessary to incorporate HRA results, linking specific human errors to final accident outcomes.

Furthermore, studies have employed linear methods such as Event Tree Analysis (ETA) and Bow-Tie Analysis and the Fine-Kinney Method, as well as nonlinear risk analysis methods such as FRAM (Functional Resonance Analysis Method) and STAMP (Systems-Theoretic Accident Model and Processes). Consequently, these risk analysis methods used in the literature represent a critical methodological advancement in maritime safety research. While linear risk analysis methods focus on quantifying the probability of human error and determining the location of the error within the accident chain, systemic approaches such as FRAM and STAMP highlight control deficiencies and interactions in complex maritime socio-technical systems. This diversity in risk analysis methods enables human error in maritime operations to be addressed not only through incident-based accident modeling but also through a systems-oriented approach. This dual approach is vital for a comprehensive and robust assessment of human-automation interaction risks, particularly in future operational contexts such as autonomous vessels.

4.1.6 Multi-criteria decision-making methods

Multi-criteria decision making (MCDM) methods are analytical methods used in decision-making processes to evaluate and rank alternatives by taking into account more than one criterion, which is crucial in complex maritime risk and safety assessments (Barretta et al., 2023). MCDM, which is used in various fields, is also used in different application areas in the maritime sector (Gohari et al., 2022).

In recent maritime human factor-related studies, it was observed that Analytic Hierarchy Process (AHP), Analytical Network Process (ANP), Decision-making Trial and Evaluation Laboratory (DEMATEL), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) are commonly used methods. AHP is the most frequently utilized method, based on matrices in which alternatives are compared in pairs to determine the importance weights of the criteria (Kandemir & Celik, 2021). ANP, which is an extended version of AHP, evaluates the interrelationship between criteria in addition to the hierarchical structure (Kheybari et al., 2020). DEMATEL, another method used, is an MCDM method used to analyze causal relationships between factors in complex systems and to determine the strength of these relationships (Si et al., 2018). The TOPSIS aims to find the most suitable alternative by considering the alternatives that are at the shortest distance to the positive ideal solution and at the farthest distance to the negative ideal solution (Behzadian et al., 2012).

These methods play a critical role in prioritizing human-induced risk assessments and mitigation strategies within maritime operations. Particularly in maritime research, MCDM methods offer a robust framework for the mathematical structuring and prioritization of subjective human factor data. By transforming qualitative expert judgments into quantitative weights and rankings, MCDM approaches enable the systematic comparison of competing human-related risk factors that cannot be directly measured. These methods not only identify risks but also provide a structured decision-support mechanism for prioritizing the most critical human errors, as identified based on expert opinions.

4.1.7 Studies evaluated by statistical analysis

Statistical analysis methods are analytical techniques used to evaluate the available data, determine the relationships between variables, and test hypotheses in maritime human factors research (Ali & Bhaskar, 2016). Methods such as parametric tests, non-parametric tests, correlation analyses, and data distribution tests were utilized. In studies of human factors in maritime accidents, statistical analysis plays a key role in objectively examining the effects of operational conditions, human performance variables, and experimental interventions.

Specifically, parametric tests such as T-tests, Analysis of Variance (ANOVA), and Multivariate Analysis of Variance (MANOVA) have been utilized in analyzed articles to investigate factors like operator workload or different operational scenarios in maritime simulator experiments. Conversely, non-parametric tests, including the Wilcoxon signed-rank test, the Mann-Whitney (M-W) test, the Kruskal-Wallis (K-W) test, and the chi-square test, are frequently preferred when maritime datasets do not meet the necessary statistical assumptions, which often occurs when analyzing accident patterns or crew behavior. Furthermore, assumption checks such as the Shapiro-Wilk test and Levene's test are routinely applied to ensure data validity for these analyses.

Recent studies indicate that statistical analysis methods are employed in studies related to the research topic to validate the fundamental statistical assumptions and data validity of developed hybrid models. In this context, statistical analysis functions as a critical validation layer, supporting the credibility and robustness of hybrid frameworks that integrate such as HRA, MCDM and Bayesian. These methods are particularly employed to establish an empirical foundation for complex and advanced modeling approaches.

Furthermore, statistical analysis techniques are extensively applied to analyze data obtained from simulations, maritime accident databases, and physiological and neurophysiological

measurement techniques, including electrocardiography (ECG), electroencephalography (EEG), functional near-infrared spectroscopy (fNIRS), eye-tracking technology, wearable sensors, and electrodermal activity (EDA). The integration of these statistical methods enables the quantification of cognitive workload, situational awareness, and stress-related responses, strengthening empirical insights into human performance in complex maritime socio-technical systems.

4.2 Ways forward and future research directions

In this part of the study, based on the key findings of the systematic review of literature, future directions are provided in detail. First of all, it was observed that, instead of single-method solutions and analyses, incorporating different models as hybrid approaches is becoming popular over the last years when considering human factor in maritime transportation. For the future, it is possible that an increasing number of papers will incorporate machine learning methods and risk analysis methods. Moreover, autonomous shipping is becoming the leading trend in maritime navigation. Obviously, future research will focus on errors occurring during human-machine interaction in remote control centers, instead of conventional bridge-based human errors. Nevertheless, incompatible technological concepts used between different ships, and accidents occurring for this reason, will bring the necessity of standardization requirements. Thus, it can be argued that data misalignment and communication failures between different ships during navigation increase safety risks. Moreover, the use of different technological concepts, for instance, camera-based sensors used to detect the environment, may present safety risks in bad weather conditions. This is already related to technological maturity but requires a regulation to reduce accident probability. Furthermore, the ISM (International Safety Management) Code is an already mature standard for conventional navigation and systems. In the future, real time data driven machine learning approaches will be integrated in ships. Analyzing the obtained data and correct decisions made at the right time could reduce the probability of troubleshooting and increase safety. However, a lack of standardization may lead to different approaches among companies. This shows that increasing inertia of technological developments also increases the required dynamism of regulatory framework. New regulations suggested by international associations will be modified as per the changing control concepts of ships. This is also related to the educational side. Understanding new error types is useful in developing education and training structures and protocols. Lessons in universities will be modified according to the technological future.

5. Conclusions

Despite the technological advances in the maritime industry, the human factor still plays a key role in maritime accidents. This article presents a comprehensive review to shed light on the human factor in maritime accidents from an academic perspective. While the studies in this field are evaluated through bibliometric analysis, the last five years of these studies are analyzed through systematic content analysis. This dual approach offers the opportunity to determine both the intellectual structure of the field and current methodological trends.

The bibliometric analysis results showed that academic interest in the role of human factors in maritime accidents has increased significantly in recent years. The increase in the number of publications over the years is important data supporting this situation. Moreover, China and Türkiye are the most productive countries, and the institutions and authors affiliated with them dominate this field. While “human factors”, “human error”, and “maritime safety” were identified as the most frequently used keywords, “autonomous ships”, “Bayesian networks”, “collision accidents”, “SLIM”, “evidence theory”, and “navigation safety” were identified as the prominent trends. Furthermore, the increasing focus on autonomous ships emphasizes that evaluating the human factor remains essential for new technologies and future ship operations.

In the second part of the study, the systematic content analysis of the last five years revealed that statistical methods, Bayesian networks, fuzzy logic, SLIM, and HFACS are the most widely applied methodologies. This systematic review highlights a critical methodological shift toward specialized and integrated approaches. Another important finding of the study is the increasing adoption of hybrid approaches that combine different methods. This trend is driven by the necessity to overcome the inherent limitations of single methods, such as managing uncertainty in subjective expert judgments and accurately quantifying HRA within complex maritime operational contexts. These approaches contribute to more robust and comprehensive assessments of human factors in maritime safety, while the emergence of maritime-specific models (SOHRA, HFACS derivatives) confirms the inadequacy of general safety frameworks for high-risk marine environments. Furthermore, the systematic shift toward systemic risk models (FRAM and STAMP), alongside traditional linear analyses, reflects a growing effort to analyze control deficiencies and interactions in complex maritime socio-technical systems, moving beyond single human errors to organizational and system failures.

From a practical perspective, the findings of this study provide important implications for maritime safety management and policy development. For safety management, the increasing dominance of hybrid methodologies and systemic approaches suggests that shipping companies should move beyond narrow, incident-based interpretations of human error. Instead, they should integrate these advanced, data-informed frameworks into their existing ISM protocols to better capture the multi-causal and organizational nature of modern maritime risks. From a policy perspective, the rising focus on autonomous shipping and human-machine interaction highlights an urgent need for regulatory bodies to update existing frameworks, such as the STCW Convention. Establishing standardized communication protocols and updated training requirements will be essential to support safe operations and prevent new types of human-induced accidents in increasingly digitalized maritime environments.

As a result, this study will be a guide for researchers, regulatory bodies and decision makers to evaluate the issue of human factors in maritime accidents more consciously, to understand the strengths and weaknesses of existing regulations, and to develop new regulations. The increasing focus on autonomous vessels necessitates the application of advanced systemic methods to reliably assess human-automation interaction risks in future control concepts. It will also provide a direction for future studies by revealing the current state of academic research on human factors.

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Declaration of generative AI in scientific writing

The authors used AI tools for grammar refinement of the manuscript. With or without AI applications, the authors are fully accountable for every process of the work and manuscript writing. All final edits, interpretations, and conclusions are the sole responsibility of the authors. The authors academically and ethically confirmed that the stated AI statements are true, and the authors are ultimately responsible and accountable for the contents of the published work, including the correctness of the references in the reference list.

CRedit author statement

Ferdi Çinar: Conceptualization; Methodology; Visualization, Resources; Writing-Original Draft. **Cenk Kaya:** Software; Validation; Formal analysis; Investigation, Writing-Original Draft. **Emre Akyüz:** Supervision; Conceptualization. **Hakan Demirel:** Supervision; Conceptualization.

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