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Decision-making in the maritime deep-sea segments – a systematic literature review on the knowledge base for prevention and mitigation of accidents

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Abstract

Maritime deep-sea shipping accounts for 80% of global trade but continues to experience accidents. Although research exists on specific prevention and mitigation technologies, methodologies, and process improvements, there are no comprehensive reviews of the knowledge base on how these studies affect decision-making in maritime. This study brings together research results and strategies for transferring research results to stakeholders involved in decision-making for the prevention and mitigation of accidents. The output of this review is shaped by a simplified typology for decision-making settings, a definition of risk information, and a state-of-the-art risk theoretical foundation. A Systematic Literature Review (SLR) was conducted following PRISMA guidelines, analyzing 33 reports from the WoS, Scopus, and EBSCO databases. Two gaps in the current knowledge base were identified: (1) limited focus on operational decision-making (only 3% of reports had operational focus) and (2) poor translation of risk information across the decision-making settings (only 10% of reports discussed strategies for transfer of research results to end recipients). These gaps could reduce the relevance of research results for those dealing with operational risks at sea in deep-sea segments. This suggests that greater attention is needed to bridge the gap between research findings and stakeholders in decision-making processes to prevent and mitigate accidents.

Keywords: Maritime, Decision-making, Risk, Deep-Sea

1. Introduction

Research efforts within the deep-sea segments appear underrepresented, despite the segment's significance, as these handle over 80% of global trade (UN 2024). The current research mainly focuses on the efficiency of container vessel logistics (Bai et al. 2021) and there is a lack of literature reviews in maritime research on decision-making and strategies for transferring research results to the end-users and decision-makers.

Despite significant efforts over the past decades on accident reduction via the expansion of safety compliance frameworks (Størkersen 2018), constant enhancement of the theoretical foundations of risk (Aven 2024) and increased access to data that can improve understanding of the various risks (Durlik et al. 2023). For example, groundings in Norwegian territorial waters increased by 54% (in the same period, rising from 39 in 2024 to 60 in 2025), and a 21% increase compared to the five-year average (Sdir 2025). Similar, less extreme, regional and sector-specific trends can be seen across Europe (EU 2025) and the rest of the world (Allianz 2024).

Reactiveness could be one of the explanations for this trend (Alexander 2012) with underreporting as one important factor, leading to a lack of transparency on critical failure modes (Bhattacharya 2009), resulting in an inadequate understanding of the risks (Dugan and Utne 2023). 95% of the accidents are reported as serious or catastrophic (also referred to as major accidents) (Zhang et al. 2025), and this restricted labeling creates a challenge for accurately estimating the frequencies of the various failure modes and their causes. Funding schemes are following the same pattern as seen in the reactiveness approach in the industry, where the majority of large European research projects over the past decades have focused on emergency response, such as FLARE, PALAEMON, and SAFEPASS (Puisa et al. 2021).

Another source of uncertainty in the generation of research results is the uncritical use of risk models and safety frameworks. The definitions of risk and safety suffer from a lack of shared understanding of the risk concept across disciplines (Aven 2024), resulting in a gap between risk theorists and practitioners of risk assessment. This can lead to mischaracterizations of risk and then provide misleading guidance to decision-makers (Aven 2023). Fragmentation, combined with mistrust among stakeholders and overlapping compliance regimes (including classification, statutory, audits, and vetting), complicates communication, resulting in the delay of a unified platform for effective decision-making in the maritime sector. These constraints impact the information generated for decision-making (Rosness 2009a).

Other industries, such as healthcare, have looked into decision-making and the transfer of risk information more holistically (Reale et al. 2023) and even applied the topology used in this review to demonstrate its potential to improve decision-making through education and structured, data-informed systems (Shahsavarani and Abadi 2015). The typology used in this review has been utilized in maritime research, but only as a tool to review the ISM code implementation on small work boats (fisheries) on the Norwegian coast (Størkersen 2018).

Deep-sea shipping is a high-risk industry, and decisions are often made under significant uncertainty, both epistemic (arising from limited knowledge), and aleatory (arising from the inherent complexity of operations). Without clear strategies for transferring risk information to its recipients, the purpose of risk information used for the prevention and mitigation of accidents is at best ineffective, and at worst, it may result in the promotion of accidents through the introduction of new hazards (Almklov et al. 2014).

This Systematic Literature Review (SLR) analyzes research on decision-making for accident prevention and mitigation in deep-sea segments, with a focus on strategies for transferring risk information to its recipients. Two core questions have guided the review:

> RQ1: How is the existing body of research structured in relation to decision-makers' level of authority and proximity to hazard (using a topology from Rosness (Rosness 2009a)) and
>
> RQ2: What strategies are used to transfer risk information (results from research) to the recipients of decision-making for the prevention and mitigation of accidents?

This study aims to identify research gaps by examining how the research is designed to facilitate the incorporation of results into the decision-making processes of the stakeholders involved.

The importance of this review lies in being the first to analyze this specific body of research in this manner and to present it in a simplified decision-making typology. Based on the findings, it also suggests possible directions for future research to enhance the validity and effectiveness of research results, thereby positively pushing the boundaries of knowledge on operational risk assessment in maritime.

The rest of the paper is structured as follows: Chapter 2 presents the SLR methodology and data collection and analysis framework, Chapter 3 presents the main results, Chapter 4 presents the discussion of the results, Chapter 5 presents the conclusion, and Further Research and Limitations follow in the last Chapters.

2. Methodology of the systematic review and Analysis Framework

2.1. Step 1: Identification of records

Systematic reviews are a powerful way to identify what is known and what is unknown about a topic, and the main goal should be to present information rather than to give definitive answers (Briner et al. 2009). To enhance quality and transparency, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was used (Page et al. 2021), and it is illustrated as a flow diagram in Figure 1.

The motivation for the review is built into the research questions and aim, which define the scope by outlining the types of literature, themes, and contexts included or excluded. The three academic databases, Scopus, Web of Science (WoS), and EBSCO Academic, were selected for their broad and complementary disciplinary coverage. These databases are not exhaustive of all those available, but are commonly used through academic libraries and focus on peer-reviewed (and hence high-quality) outputs (Wanyama et al. 2022).

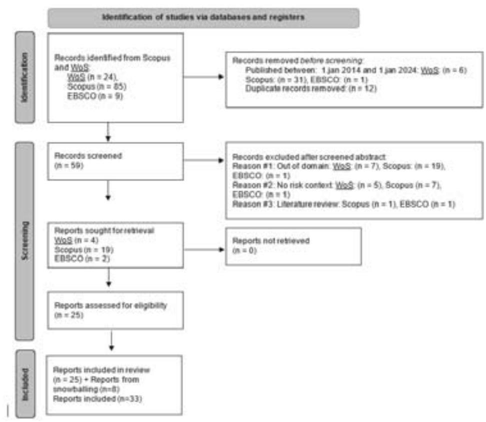

Figure 1: PRISMA flow for this SLR.

Validation of the search strategy was conducted through expert consultation with professionals from the maritime industry, who provided input on keyword selection, refinement criteria, and limiters to maintain comprehensive coverage. Emphasis was placed on studies where decision-making played a central role in accident prevention and mitigation. Keywords related to deep-sea segments, risk concepts, and decision-making terminology were combined using Boolean operators:

> (maritime OR shipping) AND (bulk OR tank* OR container OR roro OR "car carrier" OR “deep sea" OR “deep-sea OR “general cargo”) AND (risk OR safety) AND ("decision-making" OR "decision”)

This search string ensured the inclusion of studies in which risk is a central theme, while allowing for a broad range of relevant work, including those not exclusively focused on risk. The term “safety” was introduced to address the frequent overlap and ambiguity between risk and safety in maritime contexts. "Decision-making" was included to narrow the results to fit the RQ's.

The identification phase resulted in 118 records, of which 12 duplicates were removed. Titles and abstracts were then assessed against predefined eligibility criteria, excluding studies unrelated to maritime operations, studies focused on port logistics or financial risk, conceptual work lacking operational relevance, and literature reviews.

2.2. Step 2: Screening of the research records

The screening was conducted by reviewing the titles and abstracts of each identified paper. By reducing the number of target papers, we were able to perform a more thorough analysis of the most relevant papers. This manual screening of abstracts refined the selection process by excluding studies irrelevant to risk decision-making. 59 records were retained, as seen in the PRISMA flow in Figure 1.

2.3. Step 3: Eligibility assessment of records

An Excel checklist was used to track the inclusion and exclusion decisions throughout the appraisal process, ensuring transparency. 25 reports were retrieved from the eligibility assessment, and eight reports were identified through a snowballing exercise (see the limitations chapter for more on this), resulting in 33 reports included in the full-text analysis and thematic synthesis.

2.4. Step 4: Analysis of the included reports

A thorough analysis of the eligible studies was conducted to address the research questions. The terminology is based on (Rosness 2009b), which presents a theoretical model of the decision-maker with respect to the distance to hazard and the level of authority. The terms used in the following section are derived from these ideas and concepts. To ensure transparency in the analysis process, the concepts, models, and theories used to categorize and analyze the reports are outlined in the following section.

Thematic coding involves interpreting both surface-level (manifest) and deeper (latent) content, the latter requiring subjective judgment (Belur et al. 2021). When multiple observers examine the same phenomenon, some variation in outcomes is likely, and variability between coders is expected; therefore, performing certain tests was necessary. Three reviewers independently screened six records to verify consistent application of inclusion/exclusion criteria. Additionally, three reports underwent consistency checks to verify the quality of the analysis. This consistency check strengthened the validity of the findings and minimized the potential for interpretive bias.

2.4.1. Risk information

Since risk is a concept used to describe uncertainty (Hansson and Aven 2014) and when the reduction of uncertainty is the goal for a decision-maker to prevent and mitigate accidents, the decision-making needs to be grounded in evidence and a good knowledge base (Hansson and Aven 2014). These processes rely on relevant, readily available, and clearly understandable information for the decision-makers. The challenge in creating risk information arises when data and information pass through a model, leading to the propagation of uncertainty in research results, especially when all uncertainties are treated as epistemic and expressed using classical or Bayesian probabilities. This approach is not always appropriate, as only some types of uncertainty can be meaningfully described by probabilities (e.g., the probability of flipping a fair coin is 0.5) (Aven 2020a).

For risk information to be valuable, this process needs to be transparent and understood by the recipient of the results, and to ensure comparable results across the analysis, the term "risk information" is defined as:

> "any information that can be used to achieve an improved state of knowledge about risk as a basis for making a risk-related decision." (Zhu et al. 2021).

Risk information can be understood as output from research, distinguishing it from knowledge, which is processed, organized information understood by humans (Case 2012). This means information results from research, and recipients generate knowledge. The definition shows the importance of the need for strategies to transfer research results into knowledge.

2.4.2. Decision-making typology

Figure 2 illustrates the decision-making settings, adapted from the Rosness theoretical model (Rosness 2009a) that builds on ideas from (Perrow 2011). The position (x, y) of a decision-maker is determined by two dimensions: proximity to the operational hazard (i.e., distance from the sharp-end of operations) and level of authority. Authority shapes decisions but should not be confused with power (Rosness 2009a). Companies may override regulators, and frontline workers often influence practice despite formal rules (Kaarstad et al. 2010). Legal and classification bodies also influence maritime decisions by enforcing standards and combining political and administrative roles. The description of the decision-making settings can be found in (Rosness 2009a).

2.4.3. Risk information and strategies for transfer

As Paul Slovic (Paul 2016) argues, risk is not an objective entity existing independently of human perception and culture, but rather a construct developed to help individuals comprehend and manage the inherent dangers and uncertainties of life. Although such dangers are real, there is no such thing as real risk or objective risk. This perspective, which views risk as subjective and shaped by perception, context, and social meaning, necessitates a well-planned strategy for transferring risk information from research to decision-making settings. If this perspective is applied to the analysis of the reports, the use of advanced tools such as Bayesian Neural Networks can create the illusion that greater precision resolves epistemic uncertainty (Rae et al. 2020). Using results from a risk assessment study as input into a risk analysis without considering the contextual limitations of the original research, or failing to account for uncertainty in the probability estimates, can increase the potential for misinterpretation. Discussion and provision of solutions to such issues are viewed as strategies for transferring risk information in the analysis of the reports.

3. Results

The results are organized into three parts: (1) a qualitative review of reports presented in the decision-making typology by Rosness; (2) an overview of risk information, methods, tools, and transfer strategies presented in two tables; and (3) an examination of uncertainty measurement in risk information and prevalent risk themes.

3.1. Decision-making typology results

The reports distributed across Rossness's typology are presented in Figure 2. In addition, a new category was introduced to represent Research as its own typology and recipient of risk information. Only one report demonstrates a clear operational focus, in which risk information is explicitly evaluated by the stakeholders who intend to use it. 28 (16+11+1) reports are located at a removed proximity to the hazard, whereas 11 of these are in the political arena and labeled as high level of authority.

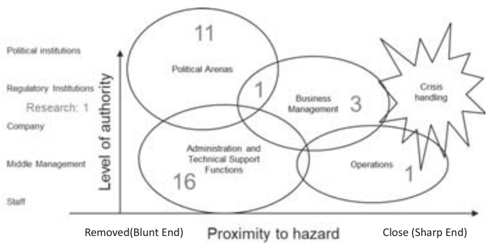

Figure 2: Decision-making setting typology (adapted from (Rosness 2009b), combining proximity to hazard and level of authority, populated with findings (the numbers) from the analysis.

3.2. Risk information and strategies for transfer results

The goal was to document the depth and robustness of the transfer strategies. The different strategies for the transfer of risk information, as presented in Table 1, were qualitatively evaluated based on the strength of their explanation: either not mentioned (Low), mentioned without further elaboration (Medium), or presented as clearly articulated strategies (High). Only three reports provide a clearly articulated approach for transferring risk information into the relevant decision-making setting. This was specifically used for operational testing, to inform simulation testing, and to update a theoretical model.

Nearly 90% of the reports lacked clarity about how their research results would be applied in a decision-making context (Low strength of strategy explanation). Reports lacking an identifiable strategy were also included in this Low category (12% of reports), even though many of them claimed that their results were valuable for multiple decision-making settings, such as:

> *"these results are important for politicians, ship managers and crew" (for this analysis it translates into: Political arenas, Admin/tech support, Operational),*

which would need more details on how to transfer the risk information to be of any immediate help for the recipients.

Table 1: Distribution of reports across decision-maker settings and the strategies used to transfer risk information. The strength of the transfer strategy explanations is rated qualitatively as: Low = not mentioned, Medium = mentioned without explanation, High = presented as clear strategies that make sense.

Decision setting	Risk information transfer strategy	Strength of strategy explanation: Low	Medium	High	Total
Administrative/tech support functions (n=16)	Incorporate into a used methodology	1			1
	Incorporate into simulation training			1	1
	Use the result to update procedures	2			2
	No identified strategy	12			12
Political arenas (n=11)	Facilitate discussion between experts		1		1
	Use results for operational testing			1	1
	Incorporate into rule-making	1			1
	Incorporate into a theoretical model	1			1
	No identified strategy	7			7
Business (n=3)	No identified strategy	3			3
Business/Political arenas (n=1)	Incorporate into rule-making		1		1
Operation (n=1)	Incorporate into a used methodology		1		1
Research (n=1)	Incorporate into a theoretical model			1	1
Total		27	3	3	33

3.3. Measurement of uncertainty in risk information and popular risk themes

Risk information was derived with the use of expert judgments in 26 out of 33 reports (as presented in Table 2). Most of these (21) combined expert judgment with mathematical methods, such as Bayesian Networks, and some (5) used them in a methodological framework. The most frequently used methods and tools are Bayesian Networks (BN), Dynamic Bayesian Networks (DBN), fuzzy logic, Deep Reinforcement Learning (DRL), and fault tree analysis. These approaches were particularly used to assess navigational and technical risks.

More structured frameworks and tools, referred to here as methodological frameworks, were applied in 9 reports, with and without expert judgement. These included the Analytic Hierarchy Process (AHP), HEART, Human Factors Analysis and Classification System (HFACS), Failure Modes, Effects, and Criticality Analysis (FMECA), Standardized Plant Analysis Risk–Human Reliability Analysis (SPAR-H), and utility analysis. These frameworks were most applied to studies focusing on human factors.

Table 2: Generic methods used to produce risk information and risk themes in focus for the research

Generic method used to produce risk information	Risk theme in focus	Total
Probabilistic mathematical models and expert judgement (n=21)	Navigational Risks risk	14
	Human Factors Risks	2
	Fire and Explosion Risks	2
	Emergency Response/Pollution to Sea	1
	Economic/social	1
	Technical Risks	1

Methodological Framework and expert judgement (n=5)	Human Factors Risks	2
	Technical Risks	2
	Navigational Risks	1
Methodological Framework (n=4)	Generic Accident Risks	1
	Cyber Risk	1
	Human Factors Risks	1
	Navigational Risks	1
Deterministic numerical mathematical model (n=1)	Navigational Risks	1
Methodological Framework and real-time operational feedback (n=1)	Human Factors Risks	1
Simulations and expert judgement (n=1)	Navigational Risks	1
Total		**33**

4. Discussions

The reports have been examined in greater depth for the selected concepts in this review, which may seem unfair, as they are interpreted through the lens of the research questions rather than the authors' original intentions. Regardless, the relevance of research results for decision-making in accident prevention and mitigation requires that these results meet their objective and be helpful to the intended recipients, especially when clearly stated in the report.

4.1. Operational gap: the challenge to access operational insight

The analysis reveals that existing research primarily focuses on the blunt-end of the operation, where distance to the actual hazard is high. It may reflect the difficulty of establishing direct contact with ships and operational realities. Regulations governing vessel access could hinder researchers' ability to collect data from real operations. One example is that, when the International Ship and Port Facility Security (ISPS) Code came into force on July 1, 2004, stricter port security regulations protected ports and ships from various hazards but also created barriers to accessing vessels and operational data.

This comes on top of a broader challenge facing researchers in risk, safety, and human factors: the limited production of empirical evidence (Rae et al. 2020). One critical issue in risk science, as discussed in the introduction, is reification. This tendency reinforces the discussed skewed research topology focus, where only one report (Akyuz et al. 2018) specifically targeted the operational decision-making setting. In that report, risk information was evaluated in real-time by a vessel captain, testing the assumptions and outcomes of theoretical models under practical conditions.

Another challenge is that some researchers (unconsciously) assume that decision-makers understand the limitations, terminology, and concepts behind the framework, methods, and models used to produce risk information. This can easily lead to misinterpretation, as discussed earlier in relation to, for example, uncertainty measures.

In addition, a "Research Decision-Maker Setting" emerged during the analysis. While this category is not part of the original typology framework, it could be proposed as a sixth decision-making setting in cases where risk information is primarily generated for academic purposes.

Theoretical frameworks abound; the safety research community frequently fails to test and adapt these models through rigorous empirical inquiry (Rae et al. 2020). This leads to an accumulation of unverified models, methods, and concepts that may be applied in practice without critical reflection, reinforcing the risk of overconfidence in models that have not been validated in real-world contexts (Aven 2020b).

Rosness acknowledged limitations in his model, noting that if not applied carefully, it can be overly abstract, and fail to capture the relevance of interaction between the decision-makers in a risk information and decision-maker setting context (Rosness 2007). Because risk and safety research relies on risk information to develop knowledge of operational uncertainties, clear communication strategies are essential. Rosness's decision-making topology provides a simple and practical high-level framework for examining how such information flows across decision-making boundaries.

The reasons for the overproduction of research on the blunt-end would require additional details not obtained through this SLR, such as funding mechanisms, the research community composition, and related factors.

4.2. Transfer gap: the challenge to transfer risk information

Bridging the gap between research findings and decision-makers requires translating complex risk information into meaningful, actionable insights tailored to each decision-maker's setting. For operational stakeholders, this may mean converting probabilities into practical guidance, clear thresholds, or illustrative scenarios that convey potential outcomes in a relatable way. For example, a research result such as:

"causation probability is 10^-4 for collisions in crossings"

may be meaningful to technical experts or analysts, but becomes hard to interpret for someone in an operational decision-making setting (e.g., a captain or crew member). This is an essential point, as the researchers of the analyzed reports explicitly identified the types of decision-makers who could benefit from their results.

Two reports on navigational risks, both oriented towards autonomous systems, offer strategies or descriptions for conveying risk information to decision-makers. As an example, one report shows three strategic directions for future development using the generated results from the research: conducting additional research involving multiple vessels, integrating human experiential knowledge, and incorporating formal navigation rules (Shen et al. 2019).

Another example is where a report explains how risk information, specifically findings from evaluating officer decision-making performance using neuropsychological indicators, can support maritime training facilities (Fan et al. 2025).

Some reports claim that their risk information is relevant across multiple decision-making settings (e.g., political and operational). Still, they fail to guide how the findings should be adapted or communicated differently across settings. Claiming broad applicability without demonstrating how to bridge the gap can reduce the usefulness of research results, and this appears to be the dominant practice of the reports in this SLR.

4.3. Uncertainty coverage and imbalanced focus

Few risk studies systematically account for uncertainty (in the context of the limitations of the risk model and possible outcomes) (Goerlandt and Montewka 2015). This result supports the findings of this analysis and may limit the interpretability of risk information. Even when uncertainty measures were applied, such as Bayesian networks, the handling of expert judgments was rarely explained or clearly defined, resulting in a lack of transparency.

For example, one report (Zhou and Yuen 2024) used expert input in a Bayesian network to rank influential risks in a container shipping context and proposed mitigation strategies. While informative, the reliance on a small number of expert judgments adds complexity and again stresses the issue of how uncertainty is handled. The mix of uncertainty assessment and value judgments using Bayesian probabilities and unexplained interpretations is problematic, supporting earlier risk science concerns (Aven 2020a).

This shows the importance of understanding the area of application for specific methods, recognizing their strengths and weaknesses, and integrating this knowledge into the research design process. Such results raise questions about the usage of advanced techniques. How can risk models provide a neutral characterization of uncertainties when subjective factors, including financial interests, may influence their inputs? This specific angle was not part of the analysis, but it remains relevant to the quality of risk information used in decision-making. A deeper reflection on this topic can be found in (Aven 2020a).

There is an imbalance in the focus of research efforts across the risk themes. Navigational risks, such as "preventing collision with ice" and "collision avoidance for multiple ships", appear in nearly 55% of the reports. In contrast, human factor risks, like "human error probabilities" and "human reliability", account for 18%, while technical risks, such as "boiler plant systems failure" and "gas freeing failures", make up 9%. The emphasis on navigational risk can stem from the availability of one of the few data sets that is consistent, understandable, and readily available, namely, AIS (Automatic Identification System) data. It is well-suited for mathematical modeling and statistical analysis, and it receives empirical feedback from specific operations (Ribeiro et al. 2023). This focus is likely reinforced by significant attention to MASS and the IMO's advancement of autonomy-related regulatory frameworks (Munim and Haralambides 2022). AIS cannot easily be translated into risk information, as it lacks critical onboard event data. For example, a vessel's chosen route may depend on operational events that are not captured in AIS and therefore remain invisible to the researcher. This lack of contextual operational data presents a significant challenge for developing effective operational risk assessment methods and tools for use on board the vessel or from shore. While there is strong momentum to fast-track autonomy towards a higher maturity level (as defined by the IMO), the progress of deep-sea autonomy can be challenged by the lack of operational research focus in the deep-sea segment.

5. Conclusion

This review identifies a gap between the generation of risk information in maritime research and its practical application in decision-making in the deep-sea segments. Applying Rosness's typology, two key findings emerge. First, an operational focus gap: more than 90% of the reports in this SLR focus on decision-making with removed proximity to the hazard, leaving operational realities underexplored. Second, there is a lack of strategies for transferring risk information from research to end recipients – the decision-makers for the prevention and mitigation of accidents.

One explanation for the lack of operational engagement may be that researchers are more inclined to recommend solutions and actions as psychological distance increases, framing such actions as "ideal" behaviors (Howell et al. 2014) (also called action hypocrisy - the tendency to advise behaviors for others that one would not personally adopt, which often occurs when distance is perceived).

A challenge with this behavior is that people make slightly riskier choices when deciding for others (Polman and Wu 2020), when they are not affected by negative consequences themselves (such as decision-makers in political arenas and business decision-making settings).

These identified gaps could diminish the relevance of research findings for decision-makers, leading to uncertainty in knowledge creation and ultimately adversely affecting the operations at sea of deep-sea vessels. This could be one part of the explanation of why accidents continue to occur despite advances in risk sciences and safety science

These findings reinforce earlier claims about the strong role of rules and procedures in supporting safety, reliability, and resilience, rather than relying on empirical results (Almklov 2018) and that research efforts can be more effective with better-designed and planned studies (Rae et al. 2020).

Interpreting risk information is crucial to decision-making in risk contexts, yet this SLR shows that research prioritizes academic progress over practical use, despite claims of relevance to end users, the decision-makers.

6. Further Research

Maritime risk research aimed at improving accident prevention and mitigation must go beyond the strict application of frameworks, tools, and models to also address the recipients of the results and their application. Future studies on decision-making and the production of risk information should prioritize co-design with end-users, including politicians, business stakeholders, regulators, technical support personnel, and vessel crews, and ensure that results are interpreted in collaboration with them.

A transparent and systematic approach to managing uncertainty is necessary across all areas of risk and safety research, acknowledging the considerable challenge of this task. Another area to investigate is how to develop strategies to translate risk information across decision-making boundaries, ensuring it remains both relevant and understandable to end users.

Interpretations of operational realities differ considerably, as demonstrated by the lack of strategies for risk information transfer and uncertainty management. Consequently, establishing a shared understanding of the interpretation of operational realities, specifically, the principles guiding operational risk management, may be a pathway towards enhancing knowledge from research on preventing and mitigating maritime accidents.

7. Limitations

This review is based on 33 reports identified through a systematic process. Although the inclusion criteria were applied consistently, some relevant studies might have been overlooked, particularly those published in non-traditional outlets or in languages other than English. Regarding the growth of the two largest producers, China and the United States showed markedly different increases in overall production, 173% for China and 6% for the US (*Nsf.Gov* 2025). This, along with the rapid rate of new publications, is a limitation of this review, potentially missing relevant studies published during the analysis period.

The qualitative assessment of how clearly and effectively risk information transfer strategies communicate involved subjective judgment. While guided by established frameworks (Rosness 2009a), some level of interpretative bias cannot be excluded. The proximity to hazard dimension, as used in our decision-making topology, is one example, as it is context-dependent, where determining whether a report addresses a specific setting (e.g., business vs. political) requires assumptions about the intended user group, which may not fully align with the report's author's original intentions. The use of tags and categories can act as analytical binders, potentially limiting alternative interpretations (Maxwell 2012). To mitigate these issues, the authors kept close dialogues with industry experts.

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