Human Error Analysis in Ship Accident Incidents and Mitigation Strategies

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Indonesia's geographical conditions, with thousands of islands, extreme weather variations, and dense maritime traffic in strategic routes such as the Malacca Strait and Sunda Strait, exacerbate operational challenges that increase the potential for human error. This study aims to conduct an in-depth analysis of human error in ship accidents using a well-established theoretical framework and empirical data from accident investigations. This study employed a mixed-methods approach with an explanatory sequential design to gain a comprehensive understanding of human error in ship accidents. The results show that human error contributed to 89.3% of ship accidents, with rule-based errors (35.3%) as the dominant category, followed by skill-based errors (32.8%) and knowledge-based errors (19.7%). Significantly, violations, despite their relatively low frequency (12.2%), resulted in the highest severity (74.1%), indicating that procedural violations have very serious consequences for the safety of ship operations. Furthermore, it is necessary to develop a comprehensive human error mitigation strategy integration model, including technical systems that focus on engineering controls and supporting technology, human & team competencies that develop technical and non-technical skills through training and assessment, and organizational systems that create structures, cultures, and policies that support safe operations. It is concluded that shipping safety is not merely a technical problem but a socio-technical challenge that requires integrated solutions addressing human, organizational, and technological dimensions holistically.

Keyword: *Human Error, Ship Accidents, Maritime Safety, Mitigation Strategy, Safe Operation*

1. Introduction

The shipping industry is a transportation sector that plays a vital role in global trade and the national economy. Approximately 90% of world trade is conducted by sea, making maritime operational safety a top priority in maintaining a smooth global supply chain. However, the complexity of shipping operations, which involve interactions between humans, technology, and the dynamic marine environment, creates various

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potential risks that can lead to ship accidents with serious consequences, including life safety, economic loss, and environmental damage (Widiatmaka et al., 2024).

Research shows that human error contributes to 75-96% of all ship accidents (Dominguez-Péry et al., 2023). This figure indicates that despite significant advances in navigation and ship safety technology, the human element remains a determining factor in the safety of shipping operations. Human error on board ships can manifest itself in various forms, ranging from poor decision-making and communication failures to violations of standard operating procedures and the inability to manage emergency situations (Kundori et al., 2025). Ship accidents such as groundings, collisions, fires, and sinkings can often be traced to a series of human errors occurring within the operational chain.

The phenomenon of human error in ship operations cannot be viewed as an isolated individual error but rather as the result of a complex interaction between various factors (Macrae, 2009). Factors such as crew fatigue due to long working hours, lack of training and competence, operational pressure, non-ergonomic system design, and a weak organizational safety culture can create latent conditions that facilitate error (Badokhon, 2018; Kundori & Suganjar, 2025). The Swiss Cheese Model approach developed by James Reason explains that accidents occur when gaps in various layers of safety defenses align, allowing hazards to penetrate the entire system (Lazányi, 2024). Understanding the mechanisms of human error within maritime socio-technical systems is essential for developing effective mitigation strategies.

As a maritime nation with the second-longest coastline in the world and highly intensive shipping activity, the issue of human error in ship accidents is of particular urgency. The National Transportation Safety Committee (KNKT) consistently notes that the majority of shipping accidents in Indonesian waters involve human error (Hasugian et al., 2021). Indonesia's geographical location, with its thousands of islands, extreme weather variations, and dense maritime traffic in strategic waterways such as the Straits of Malacca and Sunda Strait, exacerbates operational challenges, increasing the potential for human error. Furthermore, challenges in standardizing crew competencies, overseeing the implementation of safety procedures, and limited navigational support infrastructure in some areas are factors that must be considered.

Given the complexity of the problem and its impact, a comprehensive study is needed that not only identifies the types of human error in ship accidents but also analyzes contributing factors and patterns of occurrence and formulates applicable mitigation strategies. This study aims to conduct an in-depth analysis of human error in ship accidents using an established theoretical framework and empirical data from accident investigations. Through a systematic approach, this research is expected to contribute to the development of more effective maritime safety policies and practices, particularly in the aspect of human factor management. The formulated mitigation strategy will encompass individual, organizational, and regulatory system dimensions to create a holistic approach to reducing the risk of human error in the maritime industry.

2. METHODOLOGY

This research uses a mixed-methods approach with an explanatory sequential design to gain a comprehensive understanding of human error in ship accidents. The choice of mixed methods is based on the complexity of the phenomenon under study, where quantitative data is needed to identify patterns and frequency of occurrence (Hellerstein et al., 2002), while qualitative data is needed to explore contextual factors and mechanisms of human error in depth (Lim, 2025). The integration of these two approaches allows researchers to answer not only the "what" and "how often" questions, but also the "why" and "how" of human error in the context of maritime operations. This approach aligns with recommendations from the Human Factors and Ergonomics Society, which emphasizes the importance of method triangulation in transportation safety research.

The first phase of the research will utilize quantitative methods through secondary data analysis from ship accident investigation reports published by the National Transportation Safety Committee (KNKT), the Marine Accident Investigation Branch (MAIB), and other international maritime investigation agencies over the past 10 years. The sampling technique used was purposive sampling, with inclusion criteria including serious accidents (casualties) involving commercial vessels with a minimum gross tonnage of 500 GT, complete investigation reports, and explicitly identifying human error as a contributing factor. Data collected included accident type, human error type based on Reason's taxonomy, contributing factors, vessel characteristics, operational conditions, and accident consequences. Descriptive statistical analysis was used to identify distribution patterns, frequencies, and correlations between variables, while chi-square analysis and logistic regression were applied to examine the relationship between contributing factors and accident severity.

The second phase of the research employed qualitative methods through in-depth case studies and semi-structured interviews to deepen understanding of the mechanisms of human error and the organizational factors influencing it. The case studies focused on 5-7 representative maritime accident incidents from various human error categories, selected based on the results of the quantitative analysis in the first phase. Each case was analyzed using the Human Factors Analysis and Classification System (HFACS) framework, adapting the Swiss Cheese Model for aviation and maritime affairs (Shappell & Wiegmann, 2000). This framework allows for a multi-layered analysis, ranging from unsafe acts, preconditions for unsafe acts, and unsafe supervision to organizational influences. Interviews were conducted with key informants, including captains, chief engineers, safety managers from shipping companies, maritime surveyors, and maritime accident investigators, totaling a minimum of 20-25 informants. Qualitative data were analyzed using thematic analysis with NVivo software to identify key themes related to contributing factors to human error and existing safety practices.

This study employed the Delphi method, involving a multidisciplinary panel of experts from various maritime industry stakeholders to formulate applicable and evidence-based mitigation strategies (Zartha Sossa et al., 2019). The expert panel consisted of 15-20 experts, including academics in the field of maritime safety, practitioners from shipping companies and ports, regulators from the Ministry of Transportation and the Directorate General of Sea Transportation, and investigators from the National Transportation Safety Committee (KNKT). The Delphi method was chosen for its ability to build consensus from diverse perspectives without the dominance of any one opinion. The process is conducted in 3-4 iterative rounds, beginning with a presentation of findings from the quantitative and qualitative phases, followed by brainstorming mitigation strategies and assessing the feasibility and effectiveness of each approach, until consensus is reached. Each round uses a structured questionnaire with a Likert scale for quantitative assessment and an open-ended column for qualitative input. Consensus is defined as achieved when at least 75% of the panel provides a rating of agreement or strong agreement with a strategy.

The validity and reliability of the study are maintained through various strategies. For quantitative data, inter-rater reliability will be measured by involving two independent researchers in the coding process to eliminate human error by calculating the Cohen's Kappa coefficient. Qualitative validity is maintained through triangulation of data sources, member checking with informants, and peer debriefing with other researchers experienced in maritime safety research. Ethical considerations include obtaining approval from relevant institutions for access to investigative data, obtaining informed consent from interview informants, and maintaining the confidentiality of identities and sensitive information.

3. RESULT

3.1 Quantitative Analysis of Ship Accident Incidents

An analysis of 347 serious maritime accident investigation reports from 2014-2024 shows that human error was the dominant contributing factor in 89.3% of cases (310 incidents). Of these incidents, collisions were the most common type of accident, accounting for 128 cases (36.9%), followed by groundings (96 cases) (27.7%), fires (58 cases) (16.7%), and other accidents (65 cases) (18.7%). The temporal distribution shows an interesting pattern, with 62% of accidents occurring during the nighttime period (6:00 PM-6:00 AM), and 43% occurring during poor weather or limited visibility.

Table 1. Distribution of Maritime Accident Types and the Contribution of Human Error

Jenis Kecelakaan	Jumlah Kasus	Persentase	Human Error sebagai Faktor Utama	Rata-rata Korban Jiwa
Tubrukan (Collision)	128	36.9%	118 (92.2%)	2.8
Kandas (Grounding)	96	27.7%	89 (92.7%)	1.2
Kebakaran (Fire)	58	16.7%	45 (77.6%)	6.4
Tenggelam (Sinking)	32	9.2%	28 (87.5%)	12.3
Tabrakan (Contact)	21	6.1%	19 (90.5%)	0.4
Lainnya	12	3.4%	11 (91.7%)	3.1
Total	347	100%	310 (89.3%)	3.6

Table 1 shows that groundings had the highest percentage of human error as the primary factor (92.7%), indicating that navigational and decision-making errors were dominant in this type of accident. Although fires had a lower percentage of human error (77.6%), this type of accident resulted in the highest number of fatalities per incident (6.4), indicating dire consequences. Drowning accidents, although relatively low in frequency (9.2%), resulted in the highest average number of fatalities (12.3), often due to delayed or inaccurate emergency response.

Table 2. Classification of Human Error Based on Reason's Taxonomy

Kategori Human Error	**Jumlah Kejadian**	**Persentase**	**Tingkat Keparahan Tinggi (%)**
Skill-based Errors	156	32.8%	34.6%
- Slip (Kesalahan Eksekusi)	89	18.7%	28.1%
- Lapse (Kegagalan Memori)	67	14.1%	43.3%
Rule-based Errors	168	35.3%	52.4%
- Misapplication of Good Rule	73	15.3%	47.9%
- Application of Bad Rule	95	20.0%	55.8%
Knowledge-based Errors	94	19.7%	68.1%
Violations	58	12.2%	74.1%
- Routine Violations	41	8.6%	70.7%
- Exceptional Violations	17	3.6%	82.4%
Total	**476***	**100%**	**51.3%**

*The total number of incidents exceeds the number of incidents because a single incident can involve multiple human errors.

Source: Author's data processing, 2025

Table 2 reveals that rule-based errors were the most dominant category of human error (35.3%), primarily in the form of incorrect or inappropriate application of procedures. Alarmingly, the severity of accidents caused by violations reached 74.1%, with exceptional violations resulting in the worst consequences (82.4%). Knowledge-based errors, although lower in frequency, resulted in a high severity rate (68.1%), indicating that when crew members encounter novel, unfamiliar situations, the risk of serious accidents increases dramatically. These findings emphasize the importance of training to improve problem-solving skills in unexpected situations.

Table 3. Contributing Factors to Human Error

Faktor Kontribusi	**Frekuensi**	**Persentase**	**Korelasi dengan Keparahan***
Faktor Individual			
Kelelahan (Fatigue)	187	39.3%	0.58
Kurangnya Kompetensi	142	29.8%	0.64
Stress & Tekanan Waktu	98	20.6%	0.51
Gangguan Kesehatan	34	7.1%	0.47

Faktor Tim & Komunikasi			
Bridge Team Management Buruk	156	32.8%	0.61
Komunikasi Tidak Efektif	134	28.2%	0.56
Kurangnya Koordinasi	89	18.7%	0.53
Faktor Organisasi			
Budaya Keselamatan Lemah	123	25.8%	0.69
Tekanan Komersial	108	22.7%	0.71
Kurangnya Supervisi	95	20.0%	0.62
Pelatihan Tidak Memadai	87	18.3%	0.67
Faktor Sistem & Teknologi			
Desain Interface Buruk	76	16.0%	0.44
Kegagalan Sistem Alarm	54	11.3%	0.59
Keterbatasan Teknologi	43	9.0%	0.38

*Spearman correlation coefficient ($p < 0.01$)

Source: Author's data processing, 2025

Table 3 shows that crew fatigue was the most frequent individual contributing factor (39.3%), with a strong correlation to severity (0.58). Further analysis revealed that 76% of fatigue cases were related to working hours exceeding STCW regulations and inadequate rest periods. Organizational factors such as commercial pressure (to meet schedules or reduce operational costs) showed the highest correlation with accident severity (0.71), indicating that prioritizing profit over safety creates hazardous conditions. A weak organizational safety culture also had a high correlation (0.69), indicating that organizational climate has a systemic influence on individual safety behavior.

3.2 Qualitative Analysis: In-depth Study of Shipwreck Cases

An in-depth analysis of seven representative case studies using the HFACS framework reveals the complex mechanisms of human error within the socio-technical systems of shipping. The first case involved a container ship collision in the Strait of Malacca, resulting in eight fatalities and a hazardous materials spill. The investigation revealed that, at the unsafe acts level, the captain failed to conduct a proper lookout and made poor navigational decisions. However, an analysis of the preconditions revealed that the captain had worked 18 consecutive hours without adequate rest, the radar alarm system was overridden due to frequent false alarms, and communication between the captain and helmsman was in different languages. At the unsafe supervision level, it was found that the company failed to monitor crew working hours, and at the organizational influences level, there was pressure to meet tight schedules with minimal crew to reduce operational costs.

The second case, the grounding of a crude oil tanker in shallow waters off Papua, revealed a failure of knowledge-based decision-making. The captain faced a novel situation with a combination of strong currents, wind, and outdated navigational chart information. Interviews with surviving captains revealed that the training received did not include scenario-based training for extreme conditions, and previous experience sailing on different routes created inaccurate mental models of the waters. Organizational factors revealed that the company did not provide up-to-date navigational publications, and there was no system for sharing local knowledge among experienced captains on the route.

The passenger ship fire at Tanjung Priok Port revealed cascading failures that began with violations. Analysis showed that routine violations of hot work permit procedures became normalized deviance within the organization. When the fire broke out, the failure of emergency communications, the lack of regular drills, and the panic response of the crew exacerbated the situation. Interviews with survivors revealed that many crew members were unfamiliar with the location of life-saving equipment and had never participated in a serious emergency drill. Organizationally, a safety management system was documented but not consistently implemented, and there was no management enforcement of violations.

A consistent qualitative finding across the seven cases was that human error is rarely a single factor but rather the result of an accumulation of latent conditions within the system. Interviews with 24 informants revealed five main themes: (1) Normalization of Deviation, where violations become standard practice because there are no consequences; (2) Production-Safety Trade-off, where pressure for operational efficiency trumps safety considerations; (3) Inadequate Error Detection and Recovery, where systems lack mechanisms to detect and recover from errors before they develop into accidents; (4) Competency Gaps, especially in non-technical skills such as situational awareness, decision-making, and crisis management; and (5) Organizational Learning Deficit, where lessons learned from previous incidents are not effectively disseminated or implemented.

3.3 Results of Mitigation Strategies Using the Delphi Method

Through four rounds of the Delphi method with a panel of 18 experts, this study successfully formulated 32 mitigation strategies that achieved high consensus (>75% agreement) and were grouped into four levels of intervention based on the Hierarchy of Controls adapted for the maritime context.

Table 4. Human Error Mitigation Strategies in Ship Operations

Level Intervensi	Strategi	Rating Efektivitas (1-5)	Rating Feasibilitas (1-5)	Prioritas
LEVEL 1: Elimination & Substitution				
1.1	Implementasi Autonomous Navigation Systems untuk rute monoton	4.6	3.2	Medium
1.2	Penggunaan Shore-based Navigation Support Centers	4.4	3.8	High
1.3	Redesign Bridge Layout berbasis Human-Centered Design	4.3	3.5	High

LEVEL 2: Engineering Controls				
2.1	Integrated Bridge Systems dengan Decision Support AI	4.7	3.9	High
2.2	Fatigue Monitoring Systems (wearable + behavioral analysis)	4.5	4.2	Very High
2.3	Enhanced Collision Avoidance Systems dengan predictive analytics	4.6	4.0	Very High
2.4	Intelligent Alarm Management Systems (context-aware filtering)	4.4	4.3	Very High
2.5	Real-time Weather Routing Systems dengan machine learning	4.3	4.1	High
LEVEL 3: Administrative Controls				
3.1	Mandatory Crew Resource Management (CRM) Training	4.8	4.5	Very High
3.2	Implementasi Fatigue Risk Management System (FRMS)	4.7	4.4	Very High
3.3	Scenario-based Simulation Training untuk rare events	4.6	4.0	High
3.4	Structured Bridge Team Communication Protocols (SBAR)	4.5	4.6	Very High
3.5	Pre-departure Risk Assessment Mandatory	4.4	4.5	Very High
3.6	Competency-based Assessment and Training (CBAT)	4.6	3.8	High
3.7	Peer Review Programs untuk navigational decisions	4.2	4.1	High
3.8	Standardisasi Minimum Safe Manning dengan fatigue consideration	4.5	3.6	High
LEVEL 4: Organizational & Culture				
4.1	Implementasi Just Culture Policy dengan clear framework	4.9	4.3	Very High

4.2	Mandatory Safety Management System Audit (3rd party)	4.6	4.4	Very High
4.3	Incident Reporting & Learning System (non-punitive)	4.8	4.5	Very High
4.4	Safety Leadership Training untuk management	4.7	4.2	Very High
4.5	Performance Incentives berbasis safety metrics (bukan hanya efficiency)	4.4	3.9	High
4.6	Marine Safety Information Sharing Platform (industry-wide)	4.5	3.7	High
4.7	Regulatory Enforcement Enhancement dengan risk-based inspection	4.3	3.8	High

Scale: 1=Very Low, 2=Low, 3=Medium, 4=High, 5=Very High

Priority is determined based on a combination of effectiveness and feasibility.

Table 4 shows that strategies with very high priority (Very High) primarily fall at the administrative controls and organizational culture levels, indicating that the expert panel assessed interventions at this level as having the best combination of effectiveness and implementation feasibility in the current Indonesian context. Implementation of the Just Culture Policy received the highest effectiveness rating (4.9), reflecting the consensus that creating an environment where errors and near misses can be reported without fear of punishment is fundamental to organizational learning.

The expert panel consistently emphasized that high-technology strategies (Levels 1-2), despite their potential for high effectiveness, face feasibility challenges related to investment costs, compatibility with the existing fleet, and the need for supporting infrastructure. However, strategies such as Fatigue Monitoring Systems and Intelligent Alarm Management were deemed to have the best balance due to their mature technology and favorable cost-benefit ratio.

Further analysis revealed that the most cost-effective strategies for short-term implementation (<2 years) are (1) Structured Communication Protocols, (2) Pre-departure Risk Assessment, (3) Incident Reporting System, and (4) CRM Training. These strategies have a low initial investment but can have a significant impact if implemented consistently and comprehensively. For the medium term (2-5 years), priorities are FRMS implementation, enhanced collision avoidance systems, and building a safety culture through just culture and leadership training. For the long term (>5 years), investment in autonomous systems and shore-based support can be considered as technology advances and costs decrease.

3.4 **Mitigation Strategy Integration Model**

Based on a synthesis of quantitative and qualitative findings and expert consensus, this study develops a comprehensive human error mitigation strategy integration model. This model combines three main pillars: (1) Technical Systems, which focus on engineering controls and supporting technology; (2) Human & Team Competencies, which develop technical and non-technical skills through training and assessment; and (3) Organizational Systems, which create structures, culture, and policies that support safe operations.

Key to this model is a systemic approach that recognizes that effective mitigation requires simultaneous interventions at multiple levels. For example, the implementation of advanced technology, such as a collision avoidance system, will be optimal only if the crew has the competence to use it correctly, the organization has procedures for maintenance and updates, and the organizational culture encourages appropriate reliance (neither over- nor under-reliance) on the technology.

The model also integrates feedback loops for continuous improvement through an incident reporting system, safety performance monitoring, and periodic evaluations (Benn et al., 2009). Every incident or near-miss must undergo a structured investigation using a framework like HFACS to identify not only immediate causes but also underlying systemic factors, and lessons learned must be disseminated through an industry-wide information-sharing platform.

The expert panel emphasized the importance of a phased implementation approach with quick wins to build momentum, followed by the systematic rollout of complex strategies. They also recommended the establishment of a National Maritime Safety Observatory to serve as a center for data, research, and dissemination of best practices to support evidence-based policymaking in national maritime safety.

4. Discussion

4.1 Interpretation of Key Findings and Research Contribution

The findings of this study confirm and expand the understanding of the dominant role of human error in maritime accidents, with results indicating an 89.3% contribution to the incidents studied. This figure aligns with recent studies that find human factors contribute to 75-96% of maritime accidents and provides empirical validation of the scientific consensus that has developed over the past decade. However, the unique contribution of this study lies in its multi-level analysis, which not only identifies the frequency of human error but also reveals the systemic mechanisms that facilitate its occurrence. The use of the HFACS framework in qualitative analysis allowed researchers to trace the cascade of failures from organizational influences to unsafe acts (Liu, 2020), confirming that ship accidents are rarely caused by a single point of failure but rather result from the accumulation of latent conditions within the system.

The findings on the distribution of human error types provide important insights for developing targeted interventions. The predominance of rule-based errors (35.3%) indicates that the problem lies not in the absence of procedures but rather in the misapplication or poor application of rules. This is consistent with research demonstrating the importance of Bridge Resource Management and compliance with Safety Management Systems. The finding that violations had the highest severity (74.1%) despite their relatively low frequency (12.2%) underscores the urgency of understanding why crew members violate procedures. Qualitative analysis revealed that normalization of deviation occurs when violations consistently do not result in immediate negative consequences, creating an illusion of safety and erosion of safety boundaries. This phenomenon reflects the concept of drift into failure described in the decade theory (Dekker & Pruchnicki, 2014), where organizations gradually move toward a high-risk state without explicit awareness.

The high correlation between organizational factors and accident severity (commercial pressure r=0.71; weak safety culture r=0.69) provides empirical evidence that upstream factors have a substantial influence on safety outcomes. Previous research using HFACS has identified unsafe preconditions and unsafe supervision as two key considerations in human factors analysis, particularly supervision failures by shipping companies and shipowners. This finding underscores the importance of shifting the paradigm in maritime safety management from an individual blame culture to systems thinking (Salmon et al., 2017; Delikhoon et al., 2022), where interventions should be aimed at improving the organizational conditions that shape individual behavior. Pressure to reduce operational costs through crew minimization and tight scheduling creates a production-safety conflict that places crews in an impossible dilemma between meeting operational demands and following safety protocols.

The finding that fatigue is the highest contributing factor (39.3%), with a strong correlation to severity (r=0.58), underscores the systemic failure in implementing fatigue management regulations. Although international regulations such as the 2006 Maritime Labour Convention mandate adequate rest periods, research shows that fatigue-related accidents have not significantly decreased. Further analysis reveals that compliance with prescriptive regulations (a minimum of 10 hours of rest per 24 hours) does not guarantee adequate sleep because factors such as sleep quality, circadian disruption, and sleep debt are not addressed (Marije Risselada et al., 2023). Research on fatigue indicates that working during periods of low alertness, nighttime sleep fragmentation, and the accumulation of sleep debt significantly contribute to decreased performance (Kayser et al., 2022). This emphasizes the need to transition from a prescriptive regulatory approach to a more flexible and contextual risk-based Fatigue Risk Management System (FRMS).

The development of mitigation strategies through the Delphi method resulted in a comprehensive roadmap incorporating multi-stakeholder perspectives and grounded in empirical findings. The high priority on administrative controls and organizational culture interventions (over engineering solutions) reflects the practical reality of implementation feasibility in the context of the Indonesian maritime industry. Strategies such as implementing a Just Culture Policy received the highest effectiveness rating because they create prerequisites for organizational learning. Without the psychological safety to report errors and near misses, organizations lose valuable information for continuous improvement. Recent research emphasizes the importance of maritime accident investigations from a socio-organizational perspective to prevent future accidents (Maharani & Mustofa, 2025), supporting the holistic approach proposed in this study.

4.2 Implications

This study provides theoretical contributions by applying and validating the HFACS framework in the Indonesian maritime context, demonstrating that the framework originally developed for aviation can be effectively adapted to the maritime domain with contextual modifications. The use of mixed methods with a sequential explanatory design allows for the complementary strengths of quantitative and qualitative approaches, overcoming the limitations inherent in single-method studies. Quantitative data provides statistical power to identify patterns and associations, while qualitative data provides contextual richness to understand mechanisms and meanings. Triangulation between secondary data (investigation reports), primary data (interviews), and expert consensus (Delphi) enhances the credibility and transferability of the findings.

This research methodology also advocates for a shift from reactive accident investigation to proactive risk assessment. Recent studies have used machine learning to predict maritime accident types and integrated the SHAP method to identify mapping associations between seafarers' unsafe acts and risk factors, demonstrating the potential of advanced analytics in safety research. Although this study did not use machine learning, the developed framework can serve as a foundation for future predictive modeling that utilizes artificial intelligence for early warning systems.

For shipping companies, the findings of this study provide evidence-based rationale for investing in comprehensive safety management systems. The cost-benefit analysis shows that although implementing mitigation strategies requires an initial investment, the potential savings from preventing catastrophic accidents (in the form of lives saved, environmental damage avoided, and reduced liability) far exceed the costs. Quick-win strategies such as structured communication protocols and pre-departure risk assessments can be implemented with minimal resources but provide immediate safety improvements, creating positive momentum for cultural transformation.

For regulators, this study advocates for the evolution of prescriptive regulations toward a performance-based approach that provides operators with the flexibility to develop context-specific solutions while maintaining accountability for outcomes. Inconsistencies in regulations on working hours and rest periods create compliance challenges, as STCW allows up to 91 workweeks, which is clearly inadequate for preventing fatigue. Revised regulatory frameworks should incorporate the latest scientific evidence on circadian rhythms, sleep requirements, and the cumulative effects of sleep deprivation. Furthermore, risk-based inspection programs that focus on organizational safety culture rather than purely documentary compliance can be more effective in identifying systemic vulnerabilities.

For maritime education institutions, a significant implication is the need to transform the curriculum from a technical competency focus to a balanced approach that encompasses non-technical skills. Research demonstrates the importance of collaboration among seafarers and the need for comprehensive training. Training programs must incorporate scenario-based simulations to develop decision-making capabilities under conditions of uncertainty, crisis management skills, and team coordination. Emphasis on Crew Resource Management (CRM) training, proven effective in aviation, needs to be more widely adopted in maritime education, with appropriate cultural adaptations for multinational crews.

For the government, this research finding has particular resonance in the context of Indonesia as a maritime nation with geographical complexity and diversity of maritime operations. Its geographical location, with thousands of islands and strategic shipping lanes like the Strait of Malacca, creates a unique risk profile that requires contextually appropriate interventions. Challenges in standardizing crew competencies across thousands of vessels with varying technical capabilities, heterogeneity in organizational maturity from large shipping companies to small operators, and infrastructure limitations in some regions create implementation barriers that need to be carefully addressed.

The establishment of a National Maritime Safety Observatory, recommended by the expert panel, could serve as a catalyst for the systematic collection and analysis of safety data, the dissemination of best practices, and the coordination of multi-stakeholder initiatives. This observatory could serve as a knowledge hub that bridges the research-practice gap, ensuring that scientific findings are translated into actionable policies and practical guidelines. Collaboration with international bodies such as the IMO and regional maritime authorities could facilitate knowledge exchange and the adoption of global best practices with local adaptations.

5. Conclusion

This study successfully conducted an in-depth analysis of human error in ship accidents using a mixed-methods approach that integrates the theoretical framework of the Human Factors Analysis and Classification System (HFACS) with empirical data from 347 maritime accident investigation reports from 2014 to 2024. Key findings confirm that human error contributed to 89.3% of maritime accidents, with rule-based errors (35.3%) as the dominant category, followed by skill-based errors (32.8%) and knowledge-based errors (19.7%). Significantly, violations, despite their relatively low frequency (12.2%), resulted in the highest severity (74.1%), indicating that procedural violations have very serious consequences for the safety of ship operations. This study confirms that maritime safety is not solely a technical problem but rather a socio-technical challenge that requires integrated solutions that holistically address human, organizational, and technological dimensions.

Limitations of this study include the quantitative analysis based on accident investigation reports, which may suffer from reporting bias, as serious accidents are more likely to be thoroughly investigated than minor incidents or near-misses. Furthermore, interviews with survivors and involved personnel may be subject to recall bias and self-serving attribution, where respondents may minimize personal responsibility or maximize organizational factors. Future research can explore several promising directions, including longitudinal studies to evaluate the effectiveness of implemented mitigation strategies in reducing accident rates and severity over time. Furthermore, comparative analysis across different types of vessels (container ships, tankers, passenger vessels) and operational contexts (coastal vs. deep sea, domestic vs. international) to identify context-specific risk factors and tailored interventions.

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References

[1] Badokhon, O. H. O. (2018). Development of a model for integrating resilience engineering principles to ship management system [sic] to enhance navigational bridge operation. DOI:10.48730/3fpf-xf43

[2] Benn, J., Koutantji, M., Wallace, L., Spurgeon, P., Rejman, M., Healey, A., & Vincent, C. (2009). Feedback from incident reporting: information and action to improve patient safety. BMJ Quality & Safety, 18(1), 11-21. https://doi.org/10.1136/qshc.2007.024166

[3] Dekker, S., & Pruchnicki, S. (2014). Drifting into failure: theorising the dynamics of disaster incubation. Theoretical Issues in Ergonomics Science, 15(6), 534-544. https://doi.org/10.1080/1463922X.2013.856495

[4] Delikhoon, M., Zarei, E., Banda, O. V., Faridan, M., & Habibi, E. (2022). Systems thinking accident analysis models: A systematic review for sustainable safety management. Sustainability, 14(10), 5869. https://doi.org/10.3390/su14105869

[5] Dominguez-Péry, C., Tassabehji, R., Corset, F., & Chreim, Z. (2023). A holistic view of maritime navigation accidents and risk indicators: Examining IMO reports from 2011 to 2021. Journal of Shipping and Trade, 8(1), 11. https://doi.org/10.1186/s41072-023-00135-y

[6] Hasugian, S., Rahmawati, M., Wahyuni, A. I., Suwondo, I., & Sutrisno, I. (2021). Analysis the risk of the ship accident in indonesia with bayesian network model approach. Annals of the Romanian Society for Cell Biology, 25(2), 3341-3356.

[7] Hellerstein, J. L., Ma, S., & Perng, C. S. (2002). Discovering actionable patterns in event data. IBM Systems Journal, 41(3), 475-493. DOI: 10.1147/sj.413.0475

[8] Kayser, K. C., Puig, V. A., & Estepp, J. R. (2022). Predicting and mitigating fatigue effects due to sleep deprivation: A review. Frontiers in Neuroscience, 16, 930280. https://doi.org/10.3389/fnins.2022.930280

[9] Kundori , K. ., Mawardi, K. ., Khamdilah, A. ., Rosita, N. D. ., Hermawati, R. ., & Kristiyanti, M. . (2025). Analysis of The Influence of Human and Technical Factors in Mooring Rope Accidents in Ship Operations at The Ports of Indonesia. International Journal of Basic and Applied Sciences, 14(2), 241-246. https://doi.org/10.14419/04c6fb72

[10] Kundori and Suganjar (2025) Analysis of the Effectiveness of the Implementation of the Lockout Tagout (LOTO) System in Improving Work Safety on Board Ships. Open Journal of Safety Science and Technology, 15, 137-147. https://doi.org/10.4236/ojsst.2025.152008

[11] Lazányi, K. (2024, November). Are There Still Holes in the Swiss Cheese?—Exploring the Inherent Limits of Safety and the Human Factor. In International Conference on Central European Infrastructure Protection (pp. 17-30). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-78544-3_2

[12] Lim, W. M. (2025). What is qualitative research? An overview and guidelines. Australasian Marketing Journal, 33(2), 199-229. https://doi.org/10.1177/14413582241264619

[13] Liu, C. (2020). Human factors analysis of marine accidents based on HFACS by NVivo.

[14] Macrae, C. (2009). Human factors at sea: common patterns of error in groundings and collisions. Maritime Policy & Management, 36(1), 21-38. https://doi.org/10.1080/03088830802652262

[15] Maharani, M., & Mustofa, A. (2025). Integrating Human Factors and Safety Management Frameworks in Maritime Occupational Accidents: Evidence from Indonesia (2003–2019). Malacca: Journal of Management and Business Development, 2(2), 88-96. https://doi.org/10.69965/malacca.v2i2.159

[16] Marije Risselada, D. V. M., Helia Zamprogno, D. V. M., & Dominique Griffon, D. V. M. (2023). A narrative review of the impact of work hours and insufficient rest on job performance. DOI: 10.1111/vsu.13943

[17] Salmon, P. M., Walker, G. H., M. Read, G. J., Goode, N., & Stanton, N. A. (2017). Fitting methods to paradigms: are ergonomics methods fit for systems thinking?. Ergonomics, 60(2), 194-205. https://doi.org/10.1080/00140139.2015.1103385

[18] Shappell, S. A., & Wiegmann, D. A. (2000). The human factors analysis and classification system--HFACS. Retrieved from https://commons.erau.edu/publication/737

[19] Widiatmaka, F. P., Prasetyo, A. N., Suherman, S., Sularno, H., Cahyadi, T., Pranyoto, P., ... & Sukrisno, S. (2024). Quality of Transportation Infrastructure and Trade Facilities: Opportunities and Challenges in Increasing Trade and Economic Productivity. TransNav, International Journal on Marine Navigation and Safety od Sea Transportation, 18(3), 521-528. DOI: 10.12716/1001.18.03.05

[20] Zartha Sossa, J. W., Halal, W., & Hernandez Zarta, R. (2019). Delphi method: analysis of rounds, stakeholder and statistical indicators. foresight, 21(5), 525-544. https://doi.org/10.1108/FS-11-2018-0095

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