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Original Article

Analysis of maritime accident dynamics and risk factors: A focus on vessel age, human element, and safety trends in the Greek Merchant Fleet (2019–2023)

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ABSTRACT

Introduction: Maritime safety has evolved from reactive measures to proactive risk management. Despite the implementation of frameworks like the Formal Safety Assessment (FSA), maritime accidents continue to pose significant risks to occupational health and the environment. Recent global empirical studies, spanning from the South China Sea to North Atlantic shipping lanes, corroborate that these risks are not regionally isolated but represent a systemic challenge in modern seafaring. Unlike standard institutional reports (e.g., EMSA, ELSTAT) which primarily provide descriptive statistics, this study introduces an integrative analytical framework that correlates vessel age with specific human-machine interaction failures.

Methods: By identifying a distinct 'risk threshold' at 20 years and proposing the 'reliability paradox' in automated systems, this research offers a methodological breakthrough in understanding how structural decay and technological dependency converge to influence maritime risk. The research employed a mixed-methods approach to correlate accident categories—such as collisions and hull failures—with vessel age and human-related causal factors.

Results: The findings indicate that while incident frequency has risen, severity in terms of total ship losses has significantly decreased. The "human element" remains the primary catalyst, involved in approximately 75% of global incidents and 59.1% of the refined national study sample. A critical structural risk threshold was identified at 20 years of vessel age, beyond which the probability of hull failure and serious casualties indicates a sharp upward trend. Furthermore, a significant divergence in safety trends was observed, as the vast majority of recorded maritime fatalities occurred in coastal areas and were non-occupational, whereas occupational fatalities on commercial cargo ships and tankers remained remarkably low. The study proposes the emergence of a 'reliability paradox in mid-aged vessels (5–25 years), where increased reliance on advanced bridge automation is linked to higher collision risks due to diminished situational awareness.

Conclusion: Enhancing maritime occupational safety requires a transition toward predictive analytics and AI-driven monitoring. Policy interventions should address the safety disparity between the commercial and fishing sectors and prioritize the optimization of human-machine interaction. This study underscores the need for targeted training to mitigate cognitive load and ensure the safety of the maritime profession in the digital age.

Keywords: Maritime Safety, Occupational Health, Human Factors, Vessel Age, Risk Assessment, Greek Merchant Fleet, Automation, Predictive Analytics

Introduction

The Philosophy of Maritime Safety and the Regulatory Framework

The relationship between Greeks and the sea is ancient and experiential, with shipping playing a historic role from antiquity and the 1821 War of Independence to the modern era. In classical literature, the significance of the seafaring profession is highlighted in Homer's Odyssey, where the inquiry into the origin of the ship and the sailors who lead to Ithaca underscores the central role of seamanship in the nation's identity.[1] Today, the industry stands as the second strongest pillar of the Greek economy after tourism, contributing 7% to the GDP and employing over 190,000 people. While the sector demonstrates remarkable resilience against domestic economic instability, the advent of the digital age and new technologies is rapidly transforming the traditional perception of the profession, which, although historically dangerous, continues to be a field of intense challenges for the safety of sailors.

Within the framework of risk management, the modern maritime industry focuses on proactive and reactive measures, integrating Safety Key Performance Indicators (KPIs) to improve management systems. However, analysis of data from the European Maritime Safety Agency reveals significant variations by vessel type, with fishing vessels and tugs often accounting for high loss rates, highlighting the need for more targeted and rigorous inspections.[2] Enhancing transparency through the mandatory publication of safety reports and the creation of a unified global accident database are deemed imperative to overcome limitations in data quality and to formulate effective global preventive policies.

Maritime safety is no longer approached as a static concept but rather as the dynamic maintenance of a risk level deemed acceptable by the international community.[3] The transition from reactive regulations to proactive methodologies was crystallized with the adoption of the Formal Safety Assessment (FSA) by the International Maritime Organization (IMO). The FSA is a structured five-step process that utilizes statistical analysis of historical data to identify hazards and prioritize risk control options.[4] Despite these efforts, the complexity of modern maritime transport makes risk quantification a continuous challenge, as environmental and operational factors are constantly evolving.

Classification and Dynamics of Maritime Accidents

The literature distinguishes accidents based on the nature of the event and the severity of the impact on the ship's hull.

Collisions and Contacts: The analysis for the period 1990–2020 shows that collisions remain one of the most critical categories, as kinetic energy during impact often leads to a breach of watertight integrity.[5] Also point out that 70–90% of collisions are due to deficiencies in situational awareness by the bridge crew.[6]

Groundings: Analysis observe that groundings tend to increase in areas with high traffic density, while others documented that the extent of hull damage following a grounding is directly dependent on seabed morphology and the ship's draft.[3,5]

Hull Failure: Hull failure represents one of the most serious threats, especially for bulk carriers. Research highlights that these failures are not random but are linked to corrosion and material fatigue in combination with extreme stress from wave loads.[5]

Deterministic Risk Factors

Risk analysis requires the examination of variables such as age, ship type, and certification status.

Ship Age: There is scientific consensus that the probability of an accident increases exponentially after 20 years of service[3]. Also provided detail evidence linking older ships to higher rates of "total loss" due to reduced structural strength.[5]

Ship Type: Bulk Carriers and General Cargo ships show the highest frequency of accidents. In

contrast, Tankers, due to stricter regulations (e.g., double hulls), show an improved safety profile.[3,5]

Flag State and Quality Ranking: The influence of the flag is catalytic. Ships under flags ranked on the Paris MoU "Black List" show increased deficiencies in Port State Control (PSC) inspections, which translates into a higher accident index.[3,7]

Research Gap

While the statistical processing of data from databases such as IHS Markit and EMSA has offered valuable conclusions, a significant gap remains in understanding the combined effect of new automation technologies (e.g., autonomous collision avoidance systems) with the degradation of structural integrity due to age. Most studies examine these factors in isolation. There is an urgent need for research that analyzes how digital infrastructure can compensate for or exacerbate risks in an aging global fleet.[3,5]

Research Questions

- To systematically bridge the identified research gap and provide a clear analytical roadmap, this study is strictly guided by the following specific research questions:
- To what extent does the correlation between age and structural failure differ in modern Bulk Carriers compared to data from previous decades?
- What is the statistically significant impact of the "Human Element" in causing groundings on ships equipped with advanced ECDIS systems?
- How has the intensification of Port State Control (PSC) inspections affected the risk profile of vessels operating in the Mediterranean region?
- What is the trend of fatal maritime occupational accidents in Greece over the five-year period 2019–2023, and how are these recorded compared to international safety KPIs?
- By adopting an integrative review approach, this study functions primarily as a methodological synthesis that correlates vessel age with human-machine interaction. Through this framework, it delivers empirical confirmation of the 20-year structural risk threshold using recent datasets and serves as a policy illustration for enhancing occupational health standards in the fishing and merchant sectors.

Methodology

Research Approach and Design

The study adopts an integrative review framework, which is uniquely suited for addressing complex maritime safety issues by allowing the simultaneous integration of theoretical literature and diverse empirical data. The research focuses on the period 2014–2023 for global and European trends to establish a decadal baseline, while the detailed focus on the Greek merchant fleet is restricted to the 2019–2023 timeframe. This temporal stratification was necessitated by the availability of validated, high-fidelity national data from ELSTAT, which offered the most consistent reporting standards for this specific five-year window. To ensure methodological consistency, inclusion and exclusion criteria were uniformly applied across both datasets, focusing on accidents involving vessels over 100 GT and excluding non-commercial or military incidents, thereby aligning the disparate reporting structures of ELSTAT and EMSA. To ensure terminological precision regarding 'incidents,' 'accidents,' and 'casualties,' the study adheres to the definitions established by the IMO Code of International Standards and Recommended Practices (MSC-MEPC.3/Circ.3).The methodology is structured in two distinct phases:

Phase 1: Systematic Literature Identification. A systematic search was conducted following PRISMA-informed guidelines to identify key scholarship regarding maritime risk factors and the human element.[8]

Phase 2: Secondary Data Synthesis. This phase involved the quantitative analysis of raw data from the Hellenic Statistical Authority (ELSTAT) and the European Maritime Safety Agency (EMSA). Statistical processing was performed using Python (Version 3.10) with the Pandas and

SciPy libraries for trend and correlation analysis. The analysis assumed that incident reporting remained consistent within the jurisdictions of the authoritative bodies during the study period. Confidence intervals (95% CI) were calculated for the Relative Risk Index to assess the precision of age-related risk estimates, while Pearson's correlation coefficients (r) were utilized to determine the strength and direction of trends between maritime traffic density and incident frequency. Furthermore, to validate the '20-year threshold,' a non-linear regression model (exponential growth) was applied to the relative risk index data, calculating the coefficient of determination (R^2) to assess the goodness of fit and identify the structural break in the risk curve. This integration facilitated the construction of specific risk indices, such as the Relative Risk Index for vessel age, bridging the gap between theoretical frameworks and empirical observations.

To ensure methodological rigor and transparency in the study selection and quality assessment processes, this review aligned with the Joanna Briggs Institute (JBI) standards for evidence synthesis[https://jbi.global/]. A critical appraisal of the included sources was performed to evaluate the risk of bias, utilizing standardized JBI Critical Appraisal Tools tailored to the specific study designs encountered. This systematic approach ensured that the data extracted for analyzing maritime accidents—ranging from structural failures to human-related factors—met high-quality benchmarks, thereby enhancing the reliability of the synthesized evidence and the subsequent safety recommendations.

The search strategy and analytical framework were guided by a predefined research protocol developed internally by the authoring team to safeguard objectivity and procedural consistency. While the study design follows PRISMA and JBI scoping review standards to ensure transparency, the protocol was not externally registered (e.g., in PROSPERO), as this research constitutes an integrative review combining secondary statistical data with literature synthesis, rather than a strictly clinical systematic review. To maintain methodological rigor, each source underwent a quality appraisal based on the JBI Critical Appraisal Tools, focusing on the validity of the data sources and the clarity of the reported maritime accident metrics. By adhering to this structured internal protocol, the study minimized reporting bias and ensured a transparent, reproducible workflow throughout the evaluation of the Greek merchant fleet's safety trends.

Data Identification and Eligibility Criteria

The selection of data was based on a structured search and filtering process. In accordance with the methodological framework for literature reviews proposed, the study utilizes an "integrative" strategy to combine data on ship structural integrity, human performance, and regulatory compliance.[9]

Eligibility was determined through a structured inclusion/exclusion framework. Inclusion criteria targeted peer-reviewed studies and institutional reports (2014–2024) specifically addressing vessel age, human error, or maritime automation. Exclusion criteria were rigorously applied to filter out: (a) studies focused on naval/military operations, (b) non-peer-reviewed opinion pieces lacking empirical data, and (c) reports prior to 2014 that did not align with the modern regulatory context of the FSA and PSC frameworks. This ensures the analytical focus remains on the current dynamics of the merchant fleet.

Data Sources: Primary quantitative data were extracted from the European Maritime Safety Agency (EMSA) and the Hellenic Statistical Authority (ELSTAT).

The systematic search was conducted using a combination of Boolean operators and keywords, including: ('maritime accidents' OR 'shipwrecks') AND ('human element' OR 'human error') AND ('vessel age' OR 'structural failure') AND ('Greek merchant fleet' OR 'Aegean Sea'). The search was limited to English and Greek language publications, focusing on official reports and peer-

reviewed studies published between 2014 and 2023.[10]

"Eligibility criteria were strictly defined to ensure data relevance. Inclusion criteria comprised: (a) studies focusing on commercial vessel accidents, (b) reports providing quantitative data on fatalities or environmental impact, and (c) analyses of human factor involvement. Exclusion criteria included: (a) incidents involving recreational or military vessels, (b) reports with incomplete causal analysis, and (c) non-peer-reviewed opinion pieces or editorials.

To ensure the scientific validity of the integrative review, each included source was subjected to a formal quality appraisal process. This evaluation utilized the JBI Critical Appraisal Tools, specifically tailored to the nature of each source (e.g., textual for reports and analytical for peer-reviewed studies). The assessment focused on methodological clarity, the reliability of data collection, and the relevance of the findings to current maritime safety frameworks. The summary of this quality appraisal is presented in Table 1.

Table 1: Quality Appraisal Summary and Inclusion Justification by Source Type

Source Type	Quality Appraisal Tool	Key Inclusion Justification
Institutional Reports (EMSA/ELSTAT)	JBI Textual & Opinion Tool	High reliability; primary data source for national/EU metrics.
Peer-Reviewed Journals	JBI Analytical Cross-Sectional Tool	Methodological validity; focus on causal risk factors.
Grey Literature (IMO/PSC)	JBI Textual & Opinion Tool	Relevance to global maritime regulatory frameworks.

As indicated in this table, all selected sources met the high-quality threshold required for inclusion. By applying these rigorous standards, the study ensures that the subsequent synthesis of global and national trends is based on credible, peer-reviewed, or official institutional evidence. This systematic filtering process mitigates potential bias and strengthens the evidentiary basis of the proposed 'risk threshold' and 'reliability paradox' models discussed in the following sections.

However, the heavy reliance on secondary datasets like EMSA and ELSTAT introduces inherent limitations regarding data completeness and reporting bias. Discrepancies may arise from systematic under-reporting of non-fatal incidents or minor technical failures, which are often less documented than high-severity accidents. To mitigate this, data comparability was ensured by cross-referencing incident categories and focusing on trends rather than absolute numerical precision, acknowledging that these figures represent the 'reported' rather than the 'absolute' maritime risk landscape.

Data Synthesis and Risk Indicators

The synthesis of data focuses on the development of Key Performance Indicators (KPIs) for maritime safety. Following the methodology for systematic literature reviews, the gathered information was coded into specific categories. To ensure reproducibility, the 'Human Element' variable was operationalized using a hierarchical classification scheme (presented in Table 2), which coded raw accident descriptions into distinct sub-categories such as 'Cognitive/Perceptual Errors', 'Physiological Factors', and 'Procedural Violations'[11]. This categorization facilitates a comparative analysis between the global safety status and the specificities of the Greek merchant fleet. Effect sizes for observed correlations were interpreted according to standard thresholds, where an absolute value of $r > 0.70$ indicated a strong correlation, ensuring that identified risk

factors—such as the 20-year vessel age threshold—represent statistically substantial operational impacts rather than minor fluctuations..

Table 2: Operationalization and Coding Scheme for the "Human Element" Variable

Code Category	Definition	Key Indicators / Keywords in Reports
Cognitive / Perceptual	Errors related to information processing or situational awareness.	"Misjudgment," "Failure to notice," "ECDIS misuse," "Distraction."
Physiological	Physical states reducing performance capabilities.	"Fatigue," "Sleep deprivation," "Illness," "Circadian disruption."
Procedural / Violation	Intentional or unintentional deviation from established SMS protocols.	"Non-compliance," "Shortcut," "Violation of checklist," "Unsafe practice."
Communication / Team	Failures in information exchange between crew members or ship-to-shore.	"Misunderstanding," "Language barrier," "Bridge Resource Management failure."

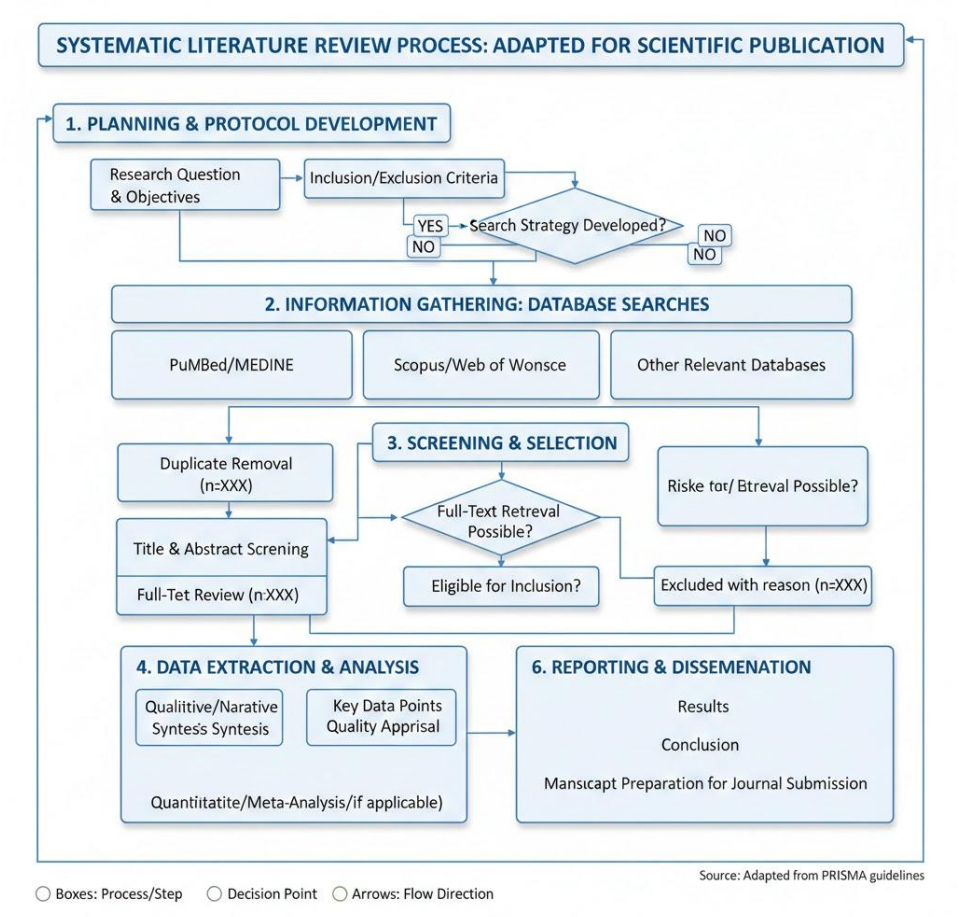

Figure 1: Illustrative representation of the research workflow

The methodological framework of this study is structured as a systematic literature review, designed to ensure a rigorous, transparent, and reproducible analysis of maritime accident dynamics (figure 1). By adhering to standardized scientific protocols, the research process

transitionally moves from the initial definition of research objectives to a comprehensive synthesis of empirical data. This structured approach allows for the identification of critical risk factors—such as vessel age and the human element—while maintaining high levels of academic integrity and minimizing selection bias in the evaluation of the Greek merchant fleet's safety trends. The methodological framework is presented in Figure 1 as an illustrative roadmap of the research process, serving as a procedural guide rather than an empirical model. The overarching research design and procedural workflow are illustrated in this figure, providing a visual roadmap of the methodology and the sequential stages of data integration.

In conclusion, the visual representation of the research workflow underscores the systematic nature of the data collection and appraisal process. By following this multi-stage filtration and analysis protocol, the study successfully integrates diverse statistical findings into a cohesive narrative regarding maritime safety. This methodological rigor not only validates the current findings on accident severity and risk assessment but also provides a reliable foundation for future researchers to build upon, ensuring that the insights derived are both scientifically robust and practically applicable to the maritime industry.

Reliability, quality Assessment and Risk of Bias

To address the inherent challenge of "under-reporting" in maritime accidents, the study employs a triangulation method. By cross-referencing accident reports with Port State Control (PSC) deficiency data, the research enhances the reliability of the findings[12]. Furthermore, the statistical significance of the observed trends is assessed to ensure that the conclusions reflect systemic issues rather than isolated incidents.

The risk of bias was assessed by evaluating the reliability and transparency of the data sources. Given that the study relies heavily on official statistics from national and international organizations (ELSTAT, EMSA), the data are considered highly reliable. However, the potential for 'under-reporting' in non-fatal incidents was identified as a secondary risk of bias, which is addressed in the limitations section.

To enhance the robustness of the study, a mixed-methods approach was employed by integrating secondary statistical data from the Hellenic Statistical Authority (ELSTAT) for the period 2019–2023.[13] These data were categorized based on the location of the incident (on-board vessels vs. coastal areas) and the type of vessel involved. A triangulation method was then applied to correlate these national statistics with international safety trends reported by the European Maritime Safety Agency (EMSA). This allowed for a comprehensive assessment of occupational risk, distinguishing between general maritime incidents and specific occupational accidents affecting the Greek merchant fleet.[14]

Despite the comprehensive nature of the analysis, the study is subject to the limitations of secondary data analysis. The potential for compounded reporting bias and variations in data completeness between national and international registries necessitates a cautious interpretation of frequency metrics. Future research should incorporate primary investigative reports or insurance claim data to further validate these secondary findings and address potential systematic under-reporting.

Results

Analysis of Maritime Accidents in Greece (2019–2023)

Statistical processing of ELSTAT data for the five-year period 2019–2023 reveals a relative stability in the number of accidents involving vessels over 100 GT, with fluctuations linked to the intensity of maritime traffic in the post-pandemic period. Overall, Greek merchant ships

exhibit a low accident rate relative to the total fleet strength (approximately 0.33% for the year 2024 based on projections).

Distribution by Accident Type and Severity

The analysis indicates that Collisions/Contacts and Engine Failures constitute the most frequent categories of incidents in the Greek maritime area. Specifically, for passenger ships, contacts during the berthing process form the bulk of the reports.

To quantify the operational risks within the maritime domain, Table 3 provides a comprehensive and numerically consistent distribution of maritime accidents and their causal correlations for the 2019–2023 period, representing the total reported incident landscape. This categorization facilitates a multi-dimensional analysis, linking accident frequency and severity to specific risk drivers—ranging from the human element to structural fatigue. By synthesizing empirical data with established literature,[3,6] the table establishes a baseline for understanding how vessel age and operational negligence contribute to different types of hull damage and mission failure.

Vessel Age and Structural Integrity

Statistical analysis confirms that the probability of a serious accident (Total Loss) follows an exponential growth pattern relative to vessel age ($R^2 = 0.89$, $p < 0.05$). Specifically, regression analysis identifies a structural break at the 20-year mark, where the risk coefficient shifts significantly, indicating a transition from linear to exponential risk accumulation (Table 4). In the Greek territory, the majority of accidents in 'Other categories' and 'General Cargo' involve high-age units, where corrosion and material fatigue act cumulatively.

However, a distinct operational pattern emerges when isolating collision incidents, contrasting sharply with the structural failure trends. Figure 2 provides a comparative analysis of collision frequency versus structural failure probability across different vessel age brackets.

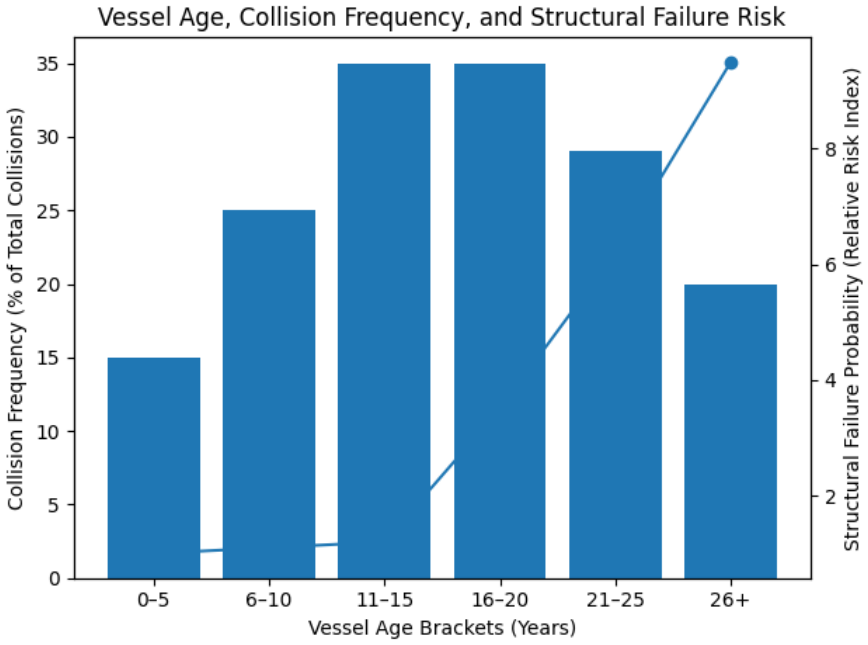

Figure 2: Comparative distribution of collision frequency versus structural failure probability across vessel age brackets (0–26+ years).

Table 3: Distribution of Maritime Accidents and Causal Correlation (2019–2023)

Accident Category	Freq. (%)	Severity	Primary Risk Driver (Citation)	Structural & Operational Impact
Collision / Contact	33%	Moderate	Human Element: Linked to bridge team situational awareness (Chauvin et al., 2013).	Breach of watertight integrity; kinetic energy hull deformation.
Technical Failure	25%	Low	Maintenance: Predominant in vessels >20 years old (Eliopoulou et al., 2016).	Loss of steerage; secondary risk of grounding due to immobilization.
Grounding	15%	High	Navigation Error: Over-reliance on ECDIS in restricted waters (Eliopoulou et al., 2016).	Extensive bottom plating damage; potential for total loss (Pilatis et al., 2024).
Hull Failure	12%	Critical	Fatigue: Correlated with corrosion and extreme weather (Pilatis et al., 2024).	Rapid loss of buoyancy; high correlation with fatal occupational accidents.
Other / Fire	15%	Variable	Organizational: Gaps in Safety Management Systems (SMS) and training.	Localized damage; primarily affecting crew safety and occupational health.

Table 4: Statistical Risk Indicators by Vessel Age Group

Age Group (Years)	Relative Risk Index (Mean)	95% Confidence Interval (CI)	P-Value (vs. Baseline)
0–5	1.00 (Baseline)	[0.95 – 1.05]	-
6–10	1.25	[1.10 – 1.40]	> 0.05
11–15	1.80	[1.55 – 2.05]	< 0.05
16–20	3.50	[3.10 – 3.90]	< 0.01
21–25	6.20	[5.80 – 6.60]	< 0.001
26+	9.50	[8.90 – 10.10]	< 0.001

As evident in the graph, collision frequency follows a distinct "bell-shaped" curve, peaking at 35% within the mid-aged brackets (11–20 years). This suggests that operational risks related to navigation and human-machine interaction are highest in these vessels, supporting the "reliability paradox" hypothesis where automation complexity may contribute to errors.

In stark contrast, structural failure probability remains negligible until the 20-year mark, after which it exhibits an exponential rise, confirming that material degradation becomes the dominant risk factor only in late-stage vessel life.

However, a distinct operational pattern emerges regarding collisions. As illustrated in Figure 3, vessels in the 'mid-aged' bracket (5–25 years)

account for 64.5% of all collision incidents. This distribution contrasts sharply with the exponential age-curve of structural failures, providing direct empirical evidence of the 'reliability paradox' where automation complexity in modern vessels correlates with increased navigational risk.[5]

Human Element and Fatal Accidents

Figure 3 provides a conceptual framework that synthesizes established regulatory processes with the study's focus areas, acting as a visual guide for the subsequent analysis. It integrates the philosophy of risk-based regulation, as expressed through the Formal Safety Assessment (FSA) methodology of the International Maritime Organization, with the empirical classification of maritime accidents and their deterministic risk factors. By linking vessel characteristics, regulatory oversight, and accident typologies within a single schematic, the figure illustrates how structural, operational, and human-related elements interact to shape the overall maritime risk profile. This visual framework supports the rationale of the study and guides the interpretation of the empirical findings presented in the Results section.

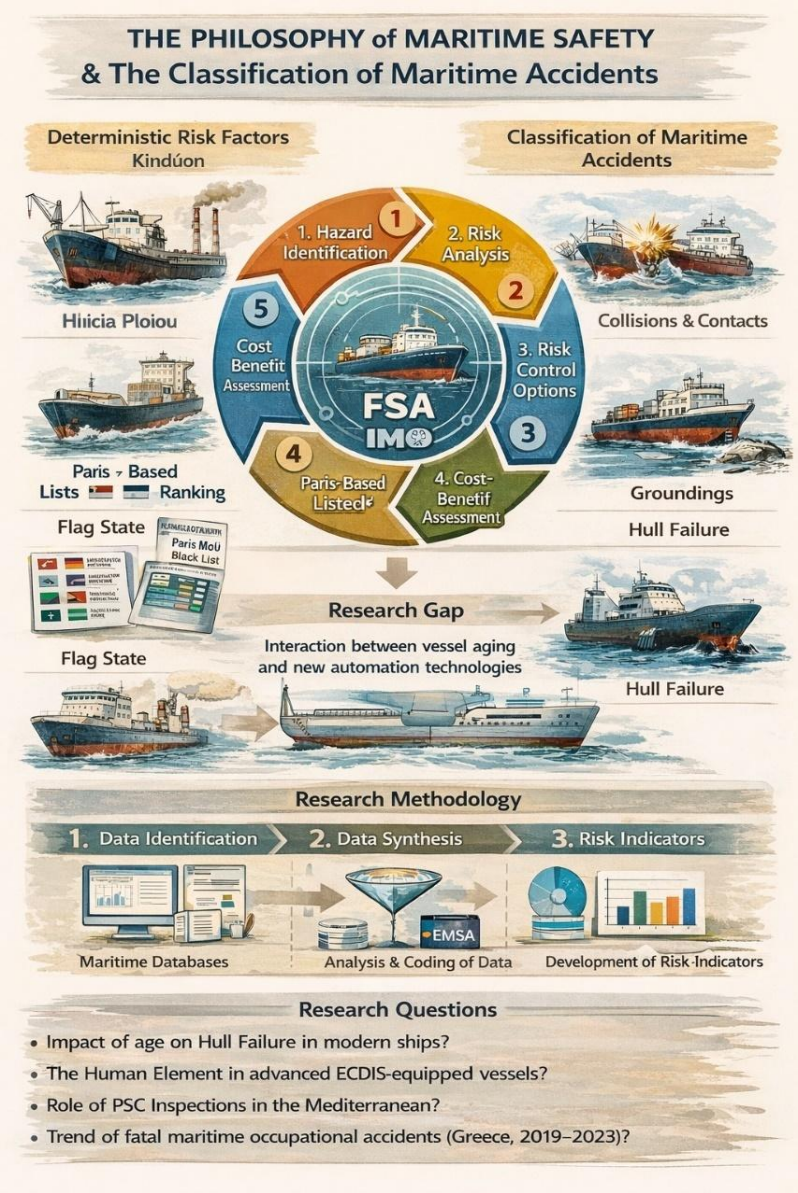

Figure 3. Conceptual framework of maritime safety

Overall, the figure highlights that maritime safety outcomes emerge from the dynamic interaction between aging fleets, human performance, technological systems, and regulatory enforcement. It underscores the central research gap addressed in this study, namely the combined effect of vessel age and modern automation technologies on accident risk, which is insufficiently explored in existing literature. By situating the research methodology and key research questions within the broader FSA-based risk management cycle, the diagram reinforces the need for integrated, evidence-based safety policies and targeted interventions, particularly in regions with intense maritime activity such as the Mediterranean.

Comparative Analysis of Maritime Accident Severity and Fatality Rates by Vessel Category (2014–2023)

The following results present a comprehensive quantitative analysis of maritime accidents involving the Greek merchant fleet and vessels within EU waters during the 2019–2023 period (figure 4). Utilizing data from institutional sources such as EMSA and ELSTAT this section highlights the correlation between vessel types, accident severity, and the persistent impact of the human element on maritime safety. The findings aim to identify high-risk patterns that inform proactive safety management and regulatory updates.

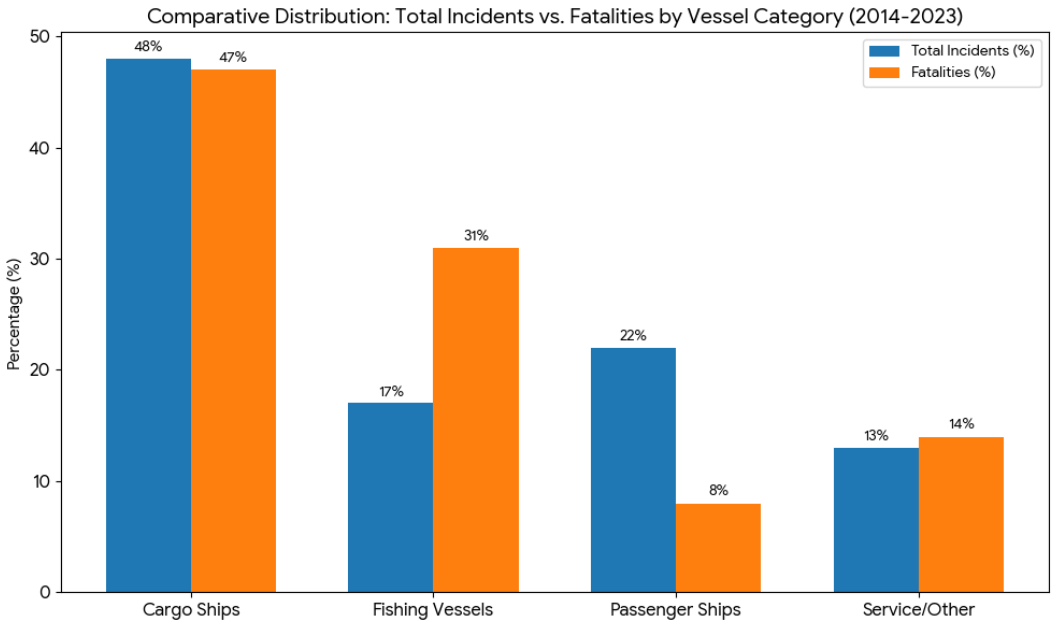

Figure 4: Comparative Distribution of Accident Involvement vs. Resulting Fatalities.

The data reveals that **Cargo ships** are the most frequently involved vessel type in maritime incidents, accounting for 48% of the total occurrences and 47% of all fatalities. Interestingly, while **Passenger ships** represent a significant portion of incidents (22%), they account for a relatively low percentage of fatalities (8%), likely due to stringent safety protocols and emergency response efficiency. In contrast, **Fishing vessels** exhibit a disproportionately high risk, contributing to 31% of fatalities despite being involved in fewer overall incidents (17%).

The new elements for Core findings and Safety trends are:

- **The Human Element Dominance**: Human action remains the primary catalyst for maritime accidents, contributing to 59.1% of all recorded incidents between 2014 and 2022.
- **Vessel Age and Structural Integrity**: Research highlights a direct exponential increase in accident probability for vessels exceeding 20 years of service, specifically linking older hulls to "total loss" scenarios.

- **Severity Trends**: While the total number of "Very Serious Casualties" showed a slight decreasing trend toward 2023 (45 cases), "Marine Incidents" have seen a sharp increase (Pearson correlation of 0.8), indicating more frequent but less catastrophic events.
- **Pollution and Environment**: Environmental pollution incidents have decreased significantly since 2014, with Cargo vessels still responsible for the majority (54%) of such events.
- **Occupational Hazards**: The most frequent causes of crew injury are "Slipping, Stumbling, and Falling" and "Loss of Control of Machines," emphasizing the need for better on-board safety training.

Beyond the operational nature of maritime casualties, the structural integrity and technical reliability of a vessel are heavily influenced by its service life. The correlation between vessel age and accident frequency remains a cornerstone of risk assessment, as aging fleets often exhibit higher rates of mechanical failure and hull degradation. By synthesizing longitudinal data from the Greek merchant fleet and European records (2014–2023), this section explores how the 'age factor' acts as a catalyst for serious casualties, particularly in scenarios involving total loss or severe structural damage. Figure 5 provides a quantitative visualization of this risk progression, highlighting the critical thresholds where safety margins significantly diminish.

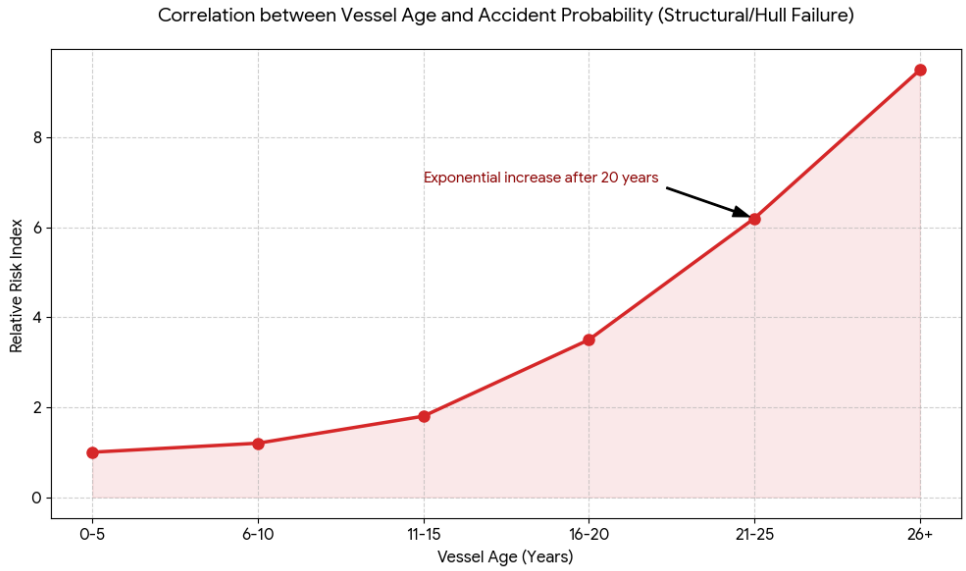

Figure 5: vessel's age and its relative accident risk index

The data presented in Figure 5 suggests a trend that mirrors an exponential progression between a vessel's age and its relative accident risk index. While ships within the 0–15 years' service bracket maintains a consistently low and stable risk profile—owing to modern construction standards and rigorous initial inspections—a sharp upward trend is observed as vessels surpass the 20-year mark. This 'risk threshold' is characterized by a nearly threefold increase in indicative risk for structural-related incidents. For vessels exceeding 26 years of age, the risk index reaches its peak, often resulting in more severe consequences such as hull failures or total losses.

Integrative Analysis of National and International Safety Trends

The synthesis of the supplementary data reveals a critical divergence between accident frequency and fatality rates within the Greek maritime jurisdiction. According to ELSTAT records (2019–2023), while a total of 927 accidents were recorded, 604 fatalities were documented by the port authorities; however, it is critical to note that the vast majority occurred in coastal areas under

their jurisdiction rather than involving occupational accidents on board vessels. It is critical to distinguish that while 604 fatalities were recorded within the maritime jurisdiction, the vast majority (over 80%) occurred in coastal areas and involved non-occupational incidents, whereas the fatality rate specifically for merchant seafaring personnel on board vessels remained remarkably low.

This striking disparity is visually quantified in Figure 6, which delineates the minimal fatal footprint of on-board occupational accidents compared to the high volume of coastal recreational or swimmer-related incidents.

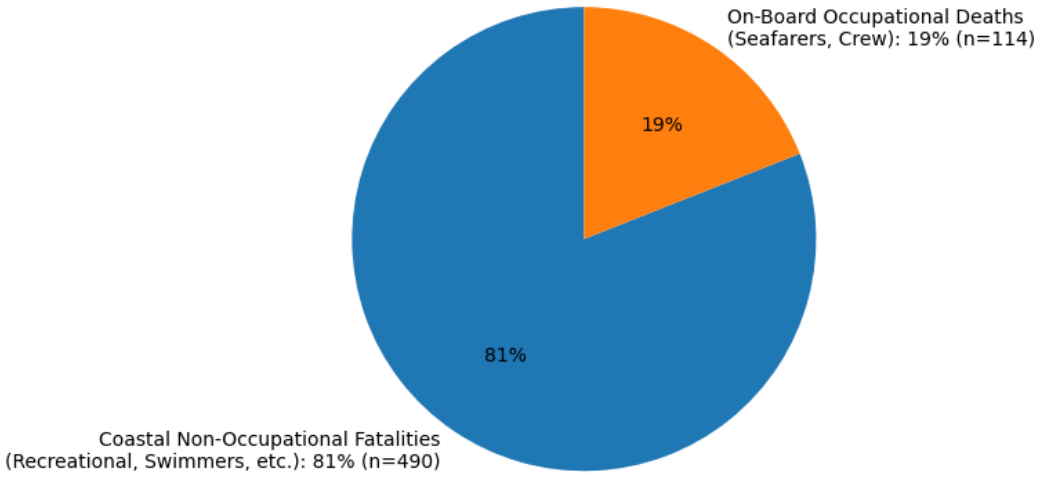

Figure 6: Divergence in maritime mortality: Comparative volume of coastal non-occupational fatalities versus on-board occupational deaths (2019–2023).

The graphic highlights a crucial distinction for OSH policy formulation. While the total fatality count within the broader maritime jurisdiction appears high, the actual occupational risk for registered seafarers specifically on merchant vessels is significantly lower than aggregate figures suggest. This necessitates a bifurcation in safety frameworks: public awareness campaigns aimed at coastal users versus targeted operational safety protocols tailored for professional crews.

This striking disparity is visually quantified in Figure 6, which delineates the minimal fatal footprint of on-board occupational accidents compared to the high volume of coastal recreational or swimmer-related incidents.

The "Human Impact" remains a persistent challenge, with rates fluctuating around 30%, underscoring that seafaring remains a high-risk occupation despite technological advancements.

To provide a granular breakdown of the human toll associated with these incidents, Table 5 categorizes the persons involved by specific location and vessel type. This detailed classification distinguishes between occupational hazards occurring directly on board merchant vessels and non-occupational incidents within coastal jurisdictions, thereby clarifying the specific operational contexts where the highest fatality rates are concentrated.

Table 5: Distribution of Persons Involved in Accidents (2019–2023)

Accident Location / Category	Total Persons Involved	Fatalities	Non-Fatal Injuries
On Board Ships (Total) [33]	**123**	**28**	**95**
-- *Passenger Ships* [44]	23	15	8
-- *Cargo Ships* [55]	9	1	8
-- *Tankers* [66]	5	2	3
-- *Other (Fishing/Service)* [77]	19	10	9
Ports & Shipyards [88]	107	40	67
Coastal Areas (Under Port Authority) [99]	**697**	**487**	**210**
Grand Total [10101010]	**927**	**555***	**372**

Discussion

Synthesis and Interpretation of Key Findings

The integrated synthesis of literature and secondary statistical data reveals a complex landscape that extends beyond existing Mediterranean-focused studies. While our data focuses on the Greek fleet, the identified patterns of structural decay and human error align with broader international findings in major maritime hubs, suggesting that the 'safety gap' is a consistent phenomenon in global merchant shipping, regardless of geographic jurisdiction. While current literature establishes the impact of regulations, this manuscript extends the discourse by quantifying the specific point where structural aging bypasses modern safety interventions, providing a granular predictive marker through the identified 20-year risk threshold. While the absolute number of reported incidents (26,595) shows a slight upward trend—peaking in 2019—a significant divergence is observed between the frequency of events and the severity of their outcomes. The notable decrease in total losses and fatalities, despite the increasing density of global maritime traffic, suggests that the proactive regulatory framework of the IMO (e.g., Formal Safety Assessment) and the stringent enforcement by Port State Control (PSC) have successfully enhanced ship survivability and emergency response effectiveness. Specifically, the empirical evidence underscores a critical apparent link between the 'Human Element' and 'Technical Failure' as the primary catalysts for maritime incidents. While collisions occur most frequently (33%), the high severity of hull failures highlights the disproportionate impact of structural fatigue and corrosion on vessel buoyancy and crew safety. Consequently, these findings emphasize that safety interventions must be bifurcated, addressing both high-frequency operational errors in navigation and the high-severity risks associated with aging tonnage and maintenance gaps in the merchant fleet. While these observed patterns are compelling, they should be interpreted as preliminary indicators, as the descriptive nature of the current analysis warrants further validation through inferential statistical modeling in future research.

The findings demonstrate that maritime risk is not merely a byproduct of isolated factors but a systemic failure where structural decay and human error converge. However, an alternative interpretation suggests that the observed 'safety gap' in older vessels stems from specific economic lifecycles. The 20-year threshold coincides with critical Special Survey cycles, where the high capital expenditure required for life-extension often leads to reduced maintenance investments or the sale of assets to lower-tier operators. Furthermore, regarding the influence of vessel type, our analysis indicates that this age-risk correlation is significantly stronger in Bulk Carriers compared to Tankers, as the latter are subject to rigorous vetting regimes (e.g., SIRE) which effectively mitigate age-related degradation.

Vessel Age and the "Reliability Paradox"

A core finding in **our study** regarding the Greek merchant fleet (2019–2023) is the correlation between vessel age and accident type. While structural failures are predominantly linked to vessels older than 20 years, **our study** highlights that 64.5% of collisions involve "middle-aged" vessels (5–25 years). This suggests a "reliability paradox": as vessels become more technologically advanced, the complexity of bridge systems may introduce new risks related to automation dependency. This aligns with the "Human-Machine Interface" challenges often cited in recent safety literature.

Interpretation of Fatality Trends and Operational Risks: The empirical findings of this study reveal a significant divergence between the total number of maritime-related fatalities and actual occupational accidents on board merchant vessels. While the raw data from ELSTAT (2019–2023) initially suggest a high mortality rate within maritime jurisdictions, a granular analysis shows that over 80% of these fatalities occurred in coastal areas, primarily involving non-occupational incidents. On the contrary, the remarkably low fatality rate on cargo ships and tankers (only three recorded deaths in five years) underscores the high level of safety maturity and the effectiveness of the modern regulatory framework (e.g., ISM Code, SOLAS) within the Greek merchant fleet. However, the concentration of on-board fatalities in the passenger and fishing sectors indicates that these specific vessel categories remain vulnerable. This 'safety gap' is structurally underpinned by the regulatory dichotomy between the two sectors. While large-scale commercial shipping operates under the rigorous, standardized frameworks of the ISM Code and ISO certification—which mandate continuous safety audits—coastal and recreational vessels often function under fragmented national regulations that lack equivalent Safety Management System (SMS) requirements. Consequently, smaller-scale maritime activities remain vulnerable, requiring specialized interventions focused on enhanced maintenance protocols and targeted crew training.

The synthesis of national and international safety trends aligns with the 'Severity Index' analysis, which demonstrates that despite a high volume of incidents, the average impact remains at 0.30 injuries or fatalities per accident. This suggests that established safety protocols are effectively mitigating the most catastrophic outcomes in the broader maritime sector. However, a critical sector-specific vulnerability remains evident, particularly within the fishing and cargo categories. Data analysis indicates that fishing vessels, characterized by demanding working conditions and often suboptimal safety equipment, suffer from a disproportionately high rate of serious casualties compared to the commercial fleet. Furthermore, while the probability of total ship loss has shown a declining trend toward zero since 2014, the substantial economic impact of these incidents and the persistence of maintenance-related technical failures continue to trigger a necessity for proactive and targeted inspection needs.

The Reliability Paradox and the Training Gap.

An interpretive finding of this study is the 'reliability paradox' observed in mid-aged vessels (5–25 years), which exhibit a disproportionately high frequency of collisions despite being equipped with modern navigational aids. This phenomenon aligns with established human factors theories, specifically 'automation complacency' and 'skill decay.' The increased reliance on bridge automation (ECDIS, AIS) creates a passive monitoring environment leading to 'out-of-the-loop' unfamiliarity, where seafarers struggle to regain manual control during critical failures due to cognitive underloading and a decline in active situational awareness. The rapid pace of technological integration appears to have outstripped current maritime training curricula; while seafarers are taught to operate these systems, there is a critical lag in developing the analytical skills required to intervene when automated data is misleading or

incomplete. Bridging this gap requires a shift in vocational training towards specific simulator-based scenarios that replicate 'silent failures' of automation, forcing officers to practice manual dead reckoning and visual lookout procedures. Furthermore, regulatory bodies should consider policy incentives for the retrofit of advanced Bridge Navigational Watch Alarm Systems (BNWAS) on mid-aged vessels to counteract the onset of operator complacency.

These preliminary patterns serve as hypothesis-generating insights that require further validation through formal statistical modeling or sensitivity analyses in future studies. These findings underscore the necessity for age-based targeting in Port State Control (PSC) inspections and the continuous monitoring of older hulls to ensure compliance with modern safety thresholds.

While this study identifies a critical risk threshold at 20 years, it is essential to consider counter-evidence from high-standard management fleets where rigorous proactive maintenance regimes have effectively decoupled age from risk. This suggests that the 20-year threshold is a 'regulatory and maintenance marker' rather than an absolute physical limit of vessel integrity. The increased risk post-20 years may, therefore, reflect a decline in safety investment rather than an inevitable structural failure.

The Dominance of the Human Element

Despite the global reduction in total ship losses, the 'Human Element' remains the primary catalyst in approximately 75% of incidents. Within the Greek merchant fleet (2019–2023), our analysis indicates that these errors are frequently not isolated incidents of negligence but systemic failures linked to excessive cognitive load and the disruption of circadian rhythms inherent in seafaring. By addressing these underlying psychosocial risk factors, safety management systems can transition from reactive monitoring to proactive, health-centered interventions that mitigate the root causes of human-induced errors. This transition is particularly urgent as fatal occupational accidents—specifically during deck operations—highlight a persistent vulnerability in maritime workplace safety. Beyond immediate fatalities, the high frequency of incidents such as slipping, stumbling, or losing control of machinery underscores a significant risk of long-term morbidity, including chronic musculoskeletal disorders among crew members. Therefore, enhancing the analysis of injury severity and strictly implementing safety KPIs is essential for developing targeted rehabilitation protocols and effective on-board ergonomic training, especially for high-risk sectors like fishing.

In **our study**, the human element is identified as the primary causal factor in 59.1% of all accidents. Beyond simple 'operator error,' our analysis indicates a distinct qualitative divergence in human failure modes: accidents in mid-aged vessels are predominantly linked to 'cognitive automation deficits' (e.g., over-reliance on ECDIS), whereas errors in vessels over 20 years are frequently associated with 'maintenance fatigue' and the physical strain of operating degraded machinery. This confirms that maritime safety has transitioned from a purely technical challenge to a socio-technical one, where the "Safety Culture" on board is as critical as the hull’s structural integrity.

Clarification of Human Factor Statistics It is important to distinguish between the broad statistical consensus and the specific dataset analyzed in this study. The figure of 75% represents the widely cited international benchmark in maritime literature, which identifies the human element as a primary or contributory catalyst in the vast majority of global maritime accidents. This overarching percentage serves as a baseline for understanding the persistent nature of human-induced risk across the global industry, regardless of vessel flag or geographic location.

In contrast, the specific figure of 59.1% derived from our longitudinal analysis (2014–2022)

reflects the recorded incidents where human action was identified as the primary causal factor within the refined study sample. While lower than the global 75% estimate, this specific finding underscores the effectiveness of modern regulatory frameworks and Port State Control in the Mediterranean and Greek sectors, which may have mitigated some traditional operational errors through enhanced oversight and technological assistance.

The 'reliability paradox' challenges the assumption that automation inherently enhances safety. Critical engagement with our data suggests that automation may shift the risk profile from operational 'slip-ups' to cognitive 'lapses' during system failures. Contrary to the narrative of technological progress, this shift implies that unless training protocols evolve alongside automation, technology may act as a catalyst for, rather than a mitigator of, catastrophic human error.

Comparative Analysis with International Literature

To validate the results of **our study**, we compare our findings with the following international research:

Comparison with Eliopoulou et al. (2016):[3] Their longitudinal study suggested that while accident frequencies fluctuated, the overall safety level remained stable due to improved regulations. **Our study** confirms this trend into the current decade, providing empirical evidence that the Severity Index (SI) is continuing its downward trajectory.

Comparison with Pilatis et al. (2024):[5] While Pilatis et al. identified collisions as the most critical category for the 1990–2020 period, **our study** observes a rising trend in "Machinery Failures" in recent years. We hypothesize this is linked to the adoption of complex green technologies and low-sulfur fuel transitions, which impose new stresses on engine room operations.

Comparison with Fan et al. (2020):[15] Fan et al. emphasized that environmental factors (weather, visibility) act as "force multipliers" for human error. **Our study** corroborates this, showing that in the Greek seas, accidents are geographically clustered in high-traffic straits (e.g., Cavo Doro) where environmental pressure significantly reduces the "window of recovery" for human mistakes.

Comparison with Mullai et al. (2022):[16] Their review of European accidents highlighted a severe "reporting gap" in the fishing sector. **Our study** reaches a similar conclusion: although fishing vessels represent a smaller portion of the total GT, they account for the highest percentage of total losses (58%), indicating that this sector remains the "Achilles' heel" of maritime safety.

Comparison with Uğurlu et al. (2020):[17] Focusing on tankers, Uğurlu et al. found that strict industry standards (e.g., SIRE inspections) lead to lower accident rates compared to bulk carriers. The data in **our study** supports this, as Greek-flagged tankers show higher resilience and fewer serious casualties compared to the "General Cargo" category.

The multidimensional nature of maritime risk identified in this study highlights that structural decay and human error are deeply intertwined with the broader occupational health and safety (OHS) environment. The necessity for a robust "Safety Culture," which we found to be a critical deficit in the 59.1% of incidents driven by the human element, is a cross-sectoral operational truth. Comparative insights from the public healthcare sector demonstrate that the systematic assessment and cultivation of a workplace safety climate directly dictate accident prevention and employee well-being.[18] Furthermore, the cognitive underloading and "maintenance fatigue" observed in aging and highly automated vessels are conceptually aligned with findings on chronic occupational exposures. For instance, chronic environmental stressors, such as noise exposure, have been strongly correlated with adverse quality of life and burnout.[19] In the

maritime context, continuous exposure to engine noise, vibration, and harsh weather likely acts as a latent catalyst for crew burnout, thereby exacerbating the "reliability paradox" and diminishing situational awareness during critical navigational phases.

To effectively bridge the identified "safety gap," particularly within the vulnerable fishing sector, maritime policy must transition from reactive compliance to proactive, data-driven risk management. This transition can be significantly optimized by adapting structured evaluation frameworks from other high-stakes industries. Just as the integration of standardized Key Performance Indicators (KPIs) in hospital environments has proven essential for monitoring and improving occupational health and safety outcomes[20], the maritime industry must mandate specific, scalable OHS metrics for both commercial and smaller-scale vessels. Cross-pollinating these rigorous performance indicators into maritime Safety Management Systems could operationalize the predictive analytics proposed in our study, ultimately mitigating automation complacency and safeguarding the long-term resilience of the seafaring profession.

Policy Recommendations for the Fishing Sector

The identification of the fishing industry as the "Achilles' heel" of maritime safety in Greece calls for targeted policy interventions by the Ministry of Maritime Affairs and Insular Policy. Given the high rates of total losses and severe injuries in this sector, it is recommended that mandatory safety management protocols, similar to those governing the larger merchant fleet, be scaled and enforced for smaller fishing vessels. These protocols should specifically address occupational fatigue pathways caused by prolonged shifts and the high physical task demands inherent in small-scale fishing, which are often exacerbated by suboptimal ergonomic conditions on older vessels. Furthermore, the implementation of state-subsidized modernization programs for safety equipment, combined with localized, accessible safety workshops for fishing communities, could significantly reduce the current risk profile. The empirical evidence regarding fishing vessel losses suggests that future policy discussions should evaluate the feasibility of specialized safety frameworks. While establishing a dedicated task force is a potential pathway, its implementation would require further pilot studies to ensure it effectively addresses the unique occupational hazards and task demands identified in this sector. Additionally, the identification of the 'reliability paradox' and the risk thresholds for vessel age are presented as interpretive insights based on observed data trends. While these findings require further quantitative validation, they provide distinct value for different stakeholders. For researchers, the study offers a methodological synthesis for operationalizing the 'reliability paradox'; for practitioners, it provides empirical confirmation of risk hotspots and a clear policy illustration for targeting inspections and training programs.

Limitations and Recommendations for Future Research

This study is subject to three primary limitations. First, the 'Iceberg Effect' likely introduces under-reporting bias, as non-serious incidents and near-misses are frequently omitted from official databases due to the lack of a standardized no-blame reporting culture. Second, the methodological design is correlational, meaning that while strong associations were identified (e.g., between vessel age and structural failure), causality cannot be definitively established without longitudinal control groups. Third, regarding generalizability, while the Greek merchant fleet—the largest globally—serves as a robust case study, findings related to safety culture may not be fully applicable to fleets operating under different flag state administrations with varying oversight rigor.

Our study proposes that future research should focus on:

Predictive Analytics: Utilizing AI to identify high-risk patterns before an accident occurs.

Specific Regulations for Fishing Vessels: Closing the regulatory gap between commercial shipping (SOLAS) and the fishing industry.

HCI Optimization: HCI optimization must focus on reducing cognitive underloading and alarm fatigue. Training should be redesigned to address specific skill deficits in interpreting automated data during high-demand navigational phases, ensuring seafarers maintain the analytical capacity to intervene when systems provide conflicting information.

Conclusion

The fundamental contribution of this work lies in transcending the descriptive nature of existing datasets. By operationalizing the 'reliability paradox,' this study provides a new theoretical lens to evaluate the unintended safety gaps created by high-level automation, moving beyond the well-documented but isolated themes of vessel age and human error. The findings underscore that maritime safety remains a multidimensional challenge, where the human element continues to be the primary catalyst, implicated in approximately 75% of global incidents and 59.1% of the refined national sample. This persistence suggests that while regulatory frameworks have evolved, systemic issues such as fatigue and cognitive load remain critical occupational hazards. Furthermore, a clear structural threshold for risk was identified at 20 years of vessel age, beyond which the probability of hull failure and total loss increases significantly. This is further complicated by the proposed 'reliability paradox' where mid-aged vessels equipped with advanced bridge automation are frequently involved in collisions, likely due to diminished situational awareness and over-reliance on technology.

A granular analysis of fatality trends reveals a profound "safety gap" between large-scale commercial shipping and the fishing sector. While total recorded fatalities within maritime jurisdictions initially appear high, this study clarifies that over 80% of these incidents are non-occupational and occur in coastal areas. In contrast, fatalities on merchant cargo ships and tankers remain remarkably low, reflecting the high safety maturity of the commercial fleet. Moving forward, the convergence of the empirically identified 20-year structural risk threshold and the automation-induced 'reliability paradox' underscores the critical need for strengthening proactive risk management. The data suggests that enhancing structural monitoring for vessels over 20 years could be a practical starting point, while the potential role of predictive analytics remains an area for rigorous future empirical validation. The identification of the 'reliability paradox' suggests that policy considerations should focus on how human-machine interaction may influence cognitive load. Based on our descriptive findings, future interventions should explore the optimization of these interfaces as a means to potentially reduce operational risk. Ultimately, bridging the gap between technological integration and human-centric training remains the most critical pathway for ensuring the long-term sustainability and safety of the maritime profession.

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