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PREFACE

Human Centered Digital Ocean: Educating Safe & Green Global Maritime Professionals

As part of the Annual General Assembly (AGA), the International Association of Maritime Universities Conference (IAMUC) brings together academics, researchers, educators, and maritime professionals from IAMU member universities worldwide to exchange knowledge, discuss recent developments, and explore future directions in maritime education, training, research, and other areas within the scope of IAMU.

IAMUC 2026 marks the 26th edition of this distinguished conference series, which began in Istanbul in 2000 and has since been hosted by maritime universities and institutions across the world. This year, the conference is hosted in Split, Croatia, bringing together the maritime academic community in a city with a rich maritime heritage and strong connections to the Adriatic, Mediterranean, and international maritime industries.

The theme of IAMUC 2026, "Human Centered Digital Ocean: Educating Safe & Green Global Maritime Professionals," reflects the profound transformation currently shaping the maritime sector. Digitalization, automation, artificial intelligence, alternative fuels, decarbonization, and other emerging technologies are rapidly changing the way ships are designed, operated, managed, and regulated. At the same time, the maritime industry remains fundamentally dependent on people. The future of shipping therefore requires not only technological innovation, but also highly competent, adaptable, safety-conscious, and environmentally responsible professionals who are able to work effectively in increasingly digital, interconnected, and rapidly changing environments.

A total of 118 Full Papers were submitted by scholars from IAMU member universities worldwide, reflecting the breadth and diversity of contemporary maritime research. Following a rigorous evaluation by an international panel of reviewers, 77 Full Papers were successfully accepted after passing the comprehensive double-blind peer-review process, including plagiarism and AI-content screening, in strict accordance with IAMU publication standards. This represents an overall acceptance rate of 65%. The accepted papers include contributions from 24 countries and 36 IAMU member universities, demonstrating the broad geographical and institutional representation of the conference and providing a diverse range of perspectives on current and emerging challenges in the maritime sector.

The contributions presented in these Proceedings cover a broad range of topics, including maritime education and training, digital transformation, maritime safety, sustainability, decarbonization, emerging technologies, and the human element. Collectively, they provide valuable insights into the ways in which maritime universities can respond to the evolving needs of the industry and prepare the next generation of maritime professionals to navigate a rapidly changing technological, environmental, and operational landscape. In doing so, the contributions reinforce the central importance of people, safety, sustainability, and innovation in shaping the future of maritime transport.

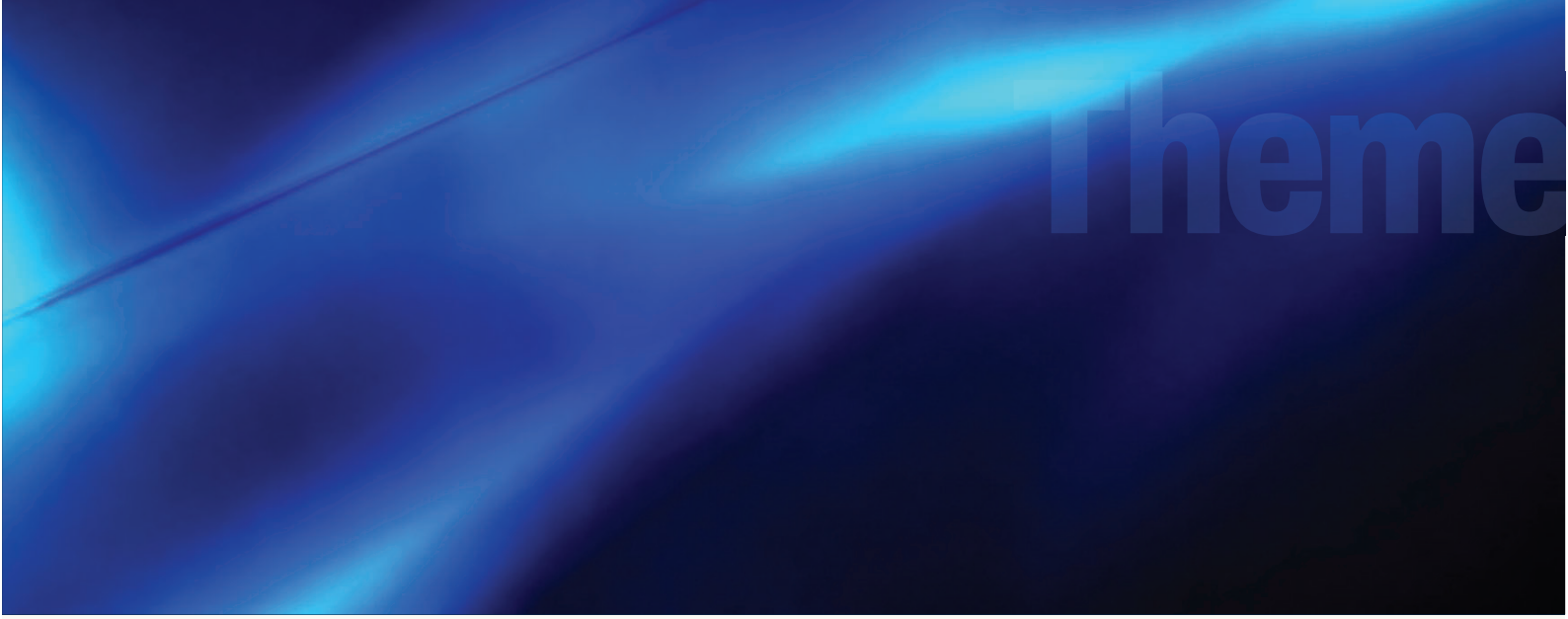
On behalf of the International Program Committee (IPC), we extend our deepest gratitude to all authors, reviewers, presenters, and participants for their valuable contributions and commitment to advancing maritime knowledge, education, and practice. We also sincerely thank our colleagues at the Faculty of Maritime Studies, the IAMU Secretariat, and all members of the organizing and program committees for their dedication, expertise, and support, which have been instrumental in making IAMUC 2026 possible.

We hope that these Proceedings will serve as a valuable contribution to the ongoing international dialogue on the future of maritime education and the maritime industry, encourage further research and collaboration among IAMU member universities, and support our shared commitment to educating safe, competent, sustainable, and future-ready maritime professionals.

Sincerely,

Tina Perić

Program Editor for IAMUC 2026



Main Theme

Human Centered Digital Ocean: Educating Safe & Green Global Maritime Professionals

General Theme Categories

Environmental Topics

Technology Topics

Economic Topics

Social Topics

Policy Topics

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Environmental Topics

Optimization Techniques in Ship Weather Routing

Görkem Ekleme [1*], Murat Selçuk Solmaz [2] and Levent Erişkin [3]

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Abstract: Approximately 80% of trade is conducted via maritime transport. Therefore, shipping operations are crucial part of global trade and accordingly, reducing transportation costs is of utmost importance. At the beginning of 2023, the International Maritime Organization (IMO) initiated a new rating system called the Energy Efficiency Existing Ship Index (EEXI) and the annual operational carbon intensity indicator (CII) index. To that end, ship weather routing has become the most crucial step in optimizing fuel consumption in accordance with IMO regulations. Incorporating decision-makers' preferences into the optimization procedure is also important since weather routing optimization algorithms provide valuable decision support to decision-makers.

It is aimed in this study to review recent weather routing optimization studies in terms of optimization techniques employed. Firstly, optimization algorithms that are used to determine optimal routings under a variety of conditions are surveyed. In our survey, optimization algorithms in terms of several dimensions are compared and classified. Then, with respect to our findings, possible research gaps regarding weather routing optimization are discussed. Lastly, prospective future recommendations that can be followed to fill these research gaps are purposed.

Keywords: ship weather routing; routing optimization; fuel consumption; maritime transportation

1. Introduction

Maritime transportation accounts for over 80 percent of volume of global trade (UNCTAD, 2021). The freight of approximately one barge is equivalent to that of 15 train cars and 58 trucks (Rodrigue et al., 2006). Consequently, shipping activities represent a critical component of international trade. Major ports of varying sizes in the Far East, such as Shanghai, Singapore, and Ningbo-Zhoushan (China), as well as in Europe, including Rotterdam and Antwerp, have capacities ranging from 14 million to 55 million twenty-foot equivalent units (TEU). The transportation activities occurring at these ports serve as the backbone of global commerce.

Despite the advantages of maritime transportation as the most economical mode of transport, efforts are continually made to identify more cost-effective methods for handling and transporting goods to maximize profit. As such, it is imperative to maintain costs at the lowest possible levels.

The majority of expenses of maritime transportation come from fuel consumption. Therefore, the most significant method for minimizing costs in maritime operations is route optimization. Effectively navigating through appropriate routes at suitable speeds, taking into account sea state and weather conditions, is essential for reducing fuel expenses. Numerous studies have been conducted to identify methods for cost reduction through the selection of optimal routes. The term "weather routing optimization" serves as the primary keyword for such research.

It is aimed in this study to conduct a comprehensive literature review on research related to "weather routing" to elucidate the existing body of knowledge and identify potential gaps in the literature. The remainder of this paper is organized as follows: Section 2 describes the methodology used for the literature search and the criteria considered to select and classify the reviewed studies. Section 3 presents a detailed discussion of the optimization techniques identified in literature. Section 4 highlights the research gaps identified through the review and outlines directions for future work. Finally, Section 5 provides conclusions for the study.

2. Methodology

This study presents a comprehensive literature review on routing optimization. The search commenced with broad keywords, including "weather routing," "routing optimization," and "ship routing." Both individual keywords and the reference lists of identified papers were utilized to expand the breadth of the search. A total of 136 studies were reviewed for this study. However, studies related to unmanned/autonomous vehicles and those that were published before the year 2020 were eliminated. Firstly, papers retained provided that they (*i*) proposed, applied, or compared one or more optimization algorithms to ship weather routing, (*ii*) were published in peer-reviewed journals or conference proceedings, (*iii*) and report quantifiable performance metrics with respect to fuel savings, or time/emission reduction. Second, full texts of the remaining papers were examined to confirm that they include sufficient methodological details for comparison. Hence, a total of 38 studies published over the past six years were ultimately selected to identify potential research directions in the relevant field. Each reviewed study is analysed based on various parameters, including author and year, optimization methods, optimization criteria, data source, vessel type, application region, and findings. The literature search was primarily conducted using major electronic databases, including ScienceDirect, IEEE Xplore, SpringerLink, and various other open-access journals.

3. Review of Optimization Techniques Used for Weather Routing

In this section, we present a brief review of optimization techniques used for weather routing. Our review is organized under five pillars: (*i*) Deterministic methods, (*ii*) Meta-heuristic methods, (*iii*) Graph-based methods, (*iv*) Artificial intelligence/machine learning-based methods, and lastly (*v*) Hybrid approaches.

Deterministic Methods are used to reach an exact solution with the same input. Therefore, if the input data remains the same, deterministic methods will always provide the same solution (Martins and Ning, 2022, p.25). Dijkstra algorithm is the best-known deterministic method and the most suitable option for short distances due to high computational time (Charalambopoulos, Xidias and Nearchou, 2023). Gkerekos and Lazakis (2020) have used the Copernicus Marine Service (CMEMS) as a data source and generated four routes from Gulf of Guinea to Marseille anchorage. Pennino et al. (2020) have used the adaptive Dijkstra algorithm to minimize the path and maximize the Seakeeping Performance Index (SPI). Novac et al. (2020) have aimed to provide economic efficiency and navigational safety by using a model ship with the Dijkstra algorithm. W. Pan et al. (2021) have used Delaunay triangulation, tangent based method, and Dijkstra algorithm with the data retrieved from the table provided in the appendix of 10th International Towing Tank Conference (ITTC) and the tide table of the region. Charalambopoulos, Xidias and Nearchou (2023) have applied Probabilistic Roadmap (PRM) and Dijkstra and Douglas–Peucker (D-P) algorithm in Aegean and Mediterranean Sea. Liu et al. (2023) have applied Dijkstra as a main method with PRM and Sampling Point Reset (SPR) function, reaching reduced waypoints from 50.54% to 62.36%. Zyczkowski and Szlapczynski (2023) have applied the modified Dijkstra algorithm to provide collision-free route only by adding 0.5-5% of the total voyage time. Ormevik et al. (2023) have used the Dijkstra algorithm to minimize the overall fuel consumption for Platform Supply Vessel (PSV). The isochrone method is a cell-free type of deterministic method. It generates routes with isochrone curves without any restriction of direction. Sasa et al. (2021) have used the modified isochrone method and seen that trajectory of National Oceanic and Atmospheric Administration (NOAA), CMEMS and the actual route is quite close to each other in severe sea conditions. Ha, Roh and Lee (2024) have aimed to minimize the collision risk in coastal waters by using an improved isochrone method. Dynamic programming (DP) which is a type of deterministic method, focuses on sub-problems to reach the main problem to reduce the computational time. As two-dimensional DP (2DDP) methods aim to optimize the route with a particular speed, three-dimensional DP (3DDP) also aims to optimize the speed and engine power to reach a more realistic solution. DP has been used in Du et al. (2022a). They have used VLCC oil tanker as an experiment ship to minimize Fuel Oil Consumption (FOC) and estimated time of arrival (ETA) with data retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF).

Meta-heuristic models are inspired by natural phenomena. They behave differently from deterministic models as they can present different solutions with the same inputs. They are gradient-free optimizers which do not require any prior information and behave like black-box (Li, Liu and Yang, 2020). One of the most prominent meta-heuristic models is the Genetic Algorithm (GA). Kuhlemann and Tierney (2020) have aimed to minimize FOC and provided over 10% fuel saving with real-coded GA. C. Pan et al. (2021) have used improved GA to minimize FOC in the North Pacific region between Yokohama and San Francisco and provided

7.84% fuel saving. Khan et al. (2022) have compared sub-algorithms of GA by using data from the Hybrid Coordinate Ocean Model (HYCOM) and NOAA in three different routes to minimize FOC, voyage time and distance. Zhou et al. (2023) have used GA with simulated annealing algorithm with a case ship and bypassed the weather warning areas. Another meta-heuristic algorithm, Ant Colony Optimization (ACO), is a pheromone-based optimization method. Each individual named as ant tries every path and leaves pheromone. The less used route with less pheromone left is eliminated. Gao et al. (2023) have conducted a modified potential field ant colony algorithm (MPFACA) with AIS data of two bulk carriers and found a smoother and more efficient route compared to traditional ACO. Particle Swarm Optimization (PSO) is also a gradient-free algorithm that aims to reach the optimum solution of the swarm. Solution of swarm consists of the solution of each particle interacting with each other (Martins and Ning, 2022, p.316). PSO has been used in the study of Du et al. (2022b). They have compared fractional order PSO (FOPSO) with traditional PSO and found that the profits are higher than those of actual navigation. Simulated Annealing (SA) generates the initial solution and begins to search for other options for the probability of finding a better solution. Afterwards, when the algorithm finds a better solution in the search area, it compares the latter to the previous one. With comparison of all options, SA can find the optimum solution. Chen, Zhang and Fu (2025) have conducted a Combined Simulated Annealing and Particle Swarm Algorithm to minimize the Energy Efficiency Operational Indicator (EEOI) and provided 5.85% to 16.93% fuel savings. Zhang, Gao and Jiang (2025) have provided nearly 15.5% shortest path with a simulated ship in a simulated region.

A graph-based algorithm is a process of computation that is conducted iteratively on a graph that consists of nodes and edges connected to each other. Among those, the A-star algorithm is the heuristic version of the Dijkstra algorithm. It aims to decrease the number of phases of search by estimating the cost from the current point to the goal point. Therefore, it is both a graph-based and a heuristic algorithm. Shin et al. (2020) have conducted improved A-star algorithm and reached 1.65% reduced ETA. Chen, Wu and Zhou (2021) have improved A-star algorithm and reduced the number of search nodes by 29.5%. Liu and Ren (2021) have proposed an improved A-star algorithm to maximize the navigational safety and to optimize turning points. Grifoll, Borén and Castells-Sanabra (2022) have aimed to minimize the sailing time with software SIMROUTE using A-star algorithm. Li et al. (2023) have used customized A* algorithm with predicted data with artificial neural network (ANN) and reached fuel saving of nearly 7.25%. The D-star algorithm is the dynamic version of A-star algorithm. It is used for dynamic and unknown regions. It can update the route by changing the cost of arcs (Stentz, 1994). In their study, Li et al. (2024) have used D star lite algorithm to optimize multiple parameters with data retrieved from ECMWF and General Bathymetric Chart of the Oceans (GEBCO) and provided a reduction of 2.32% in sailing distance. Rapidly exploring Random Tree (RRT) is a searching algorithm that deploys samples in unexplored regions and connects them with previous points, which resembles tree branches. Cao et al. (2022) have used an improved RRT algorithm with a model ship with AIS data retrieved from the FigShare platform. Gu et al. (2023) have used improved RRT algorithm with AIS data clustering of Xiamen port. Xu et al. (2025) have applied Bidirectional Adaptive Informed-Rapidly Exploring Random Tree (BAI-RRT*) and reached 20.6% lower running time and 15.3% in sampling success rate.

Artificial Intelligence (AI) based methodologies have also been utilized heavily in weather routing. Moradi et al. (2022) have conducted RL with data retrieved from Stormglass.io, which is a Global Weather Application Programming Interface (API) that provides weather forecasts to users. They have provided 6.64% fuel savings. Wu et al. (2023) have conducted a combination of Convolutional Neural Network (CNN) and transformer architecture to provide continuous model with weather data received from ECMWF and the Integrated Marine Observing System (IMOS) to increase temporal and spatial resolution. Wang et al. (2024) have used Deep Reinforcement Learning (DRL) with Theta-star algorithm to minimize fuel consumption and Greenhouse gases (GHG) and reached a reduction of three-fourths of total fuel consumption. Chen et al. (2025) have combined A* with DRL as Double Deep Q-Network (DDQN) to minimize FOC, GHG emission, voyage time, and distance. Latinopoulos et al. (2025) have compared two DRL models to minimize FOC and reached up to 12% fuel savings.

Hybrid Algorithms can be defined as mutual algorithms that are conducted subsequently or in a modified version integrated with each other to complement the disadvantages of a single algorithm. Wang, Lang and Mao (2021) have combined Dijkstra, GA and DP to minimize FOC, GHG and ETA punctuality in their study. Zhao et al. (2022) used the combination of the multi-objective particle swarm optimization (MPSO) algorithm with the GA to optimize FOC, sailing time, and navigational risk. Zhang, Wen and Tu (2023) have proposed ACO and A-star to find the shortest path and reached a 40 nm shorter path with 74.5% reduced turning points. Song

et al. (2023) have used A-star dynamic current environment algorithm (A-DCE) and Non-dominated Sorting Genetic Algorithm II (NSGA-II) with data retrieved from North American Cartographic Information Society (NACIS) and TideTech. Rafalias (2024) has compared the estimations of Deep Neural Network (DNN) and Simplified Naval Architecture Method (SNAM) for consumption, however he has used A-star algorithm and NSGA-II to reach the optimum route.

Table 1 presents some key features of 21 selected studies on weather routing optimization for ships in the years 2020 to 2025, including six dimensions: optimization algorithm, optimization criteria, data source, vessel type, application region, and conclusions. A variety of optimization algorithms are used in the articles under review, namely deterministic (Dijkstra algorithm, DP), meta-heuristics algorithms (GA and SA), graph algorithms (A* and variations of RRT), and, more recently, AI-oriented approaches (RL, and DRL). FOC and GHG are the most commonly applied optimization criteria; this is linked to increasing pressure from the IMO regarding environmental protection. Among the sources of meteorological data used in these studies, ECMWF and CMEMS stand out, whereas AIS data are used to obtain trajectories of the studied ships. A wide array of ships' types is used in the studies, namely containers, tankers, platform supply vessels, and harbour tugs; the application regions include North Atlantic, North Pacific, China Sea, and Mediterranean Sea. In quantitative terms, different algorithmic families achieve a variety of different levels of savings. Metaheuristic approaches achieve improvements ranging from 5.85% to 10%, while GA based studies report savings between 7.6% and 10% (Kuhlemann and Tierney, 2020; C. Pan et al., 2021; Khan et al., 2022). Conversely, deterministic methods seem to provide modest improvements where in Du et al. (2022a) a fuel reduction of 1.39% was reported with three-dimensional DP, and in Ormevik et al. (2023) a 4.5% reduction with a high-fidelity Dijkstra-based approach was observed. The variance of the improvement levels of different graph-based methods is significantly large, i.e., A* based algorithms report improvements ranging from 1.65% to 18% where reductions in sailing time or path length are prevalent (Shin et al., 2020; Grifoll, Borén and Castells-Sanabra, 2022). AI driven approaches, on the other hand, also present promising results. For instance, Moradi et al. (2022) reported fuel savings of 6.64% using RL. Among all, hybrid approaches have produced the most significant improvements. Combining DRL with Theta*, Wang et al. (2024) reported fuel savings of up to 74% in confined waterway environments. We would like to note that such exceptional results may be strongly influenced by specific operational settings such as narrow waterways and simplified simulation assumptions. These results highlight the need for standardized benchmarking frameworks that enable fair comparisons between different routing algorithms under equivalent operational scenarios.

4. Research Gaps and Future Work

After a careful review of the articles, as presented in Table 1, a serious research gap emerges concerning the lack of comprehensive comparisons between different algorithm families' performances based on meteorological and oceanographic variations. According to Table 1, most of the examined research compares the new algorithm to either a standard version of the algorithm itself or a historical record of the AIS signal of the reference ship used. Although the methodology yields results indicating improvement over previous approaches, it is challenging to compare the various categories of algorithms, including deterministic, meta-heuristic, graph, artificial intelligence, and hybrid techniques, and identify differences in performance among each other when subjected to the same atmospheric and sea conditions. In other words, the comparison methodology adopted fails to generate generalizable conclusions about the relative suitability of each family of algorithms.

Furthermore, the reviewed articles use various sources of data and conduct their experiments in diverse geographic locations and with varying meteorological conditions, making any attempt at cross-study comparisons futile. Indeed, this research gap becomes more significant when considering the heterogeneity of maritime operating conditions. For instance, an algorithm that yields better results in an open-sea region might operate differently in areas where there are currents, storms, and narrow waterways, as partially indicated in the increased fuel savings obtained in confined waters compared to open-sea regions, as shown in Table 1.

In light of this discussion, future research on this topic should develop systematic comparative experiments that expose the candidate algorithms to similar meteorological conditions, such as calm, normal, and adverse sea weather, in different geographic locations. Such an approach can be complemented by employing consistent evaluation metrics for fuel savings, voyage time, and GHG emissions, thereby enhancing the comparison's validity and reliability.

able 1. Brief information related to reviewed studies

Authors & Year	Optimization methods	Optimization Criteria	Data Source	Vessel Type	Application Region	Findings
Pennino et al. (2020)	Dijkstra algorithm (adaptive)	Shortest path by maximizing SPI	Global Wave Model (GWAM).	Simulated ship	North Atlantic Ocean	Improvement up to 50% of the ship seakeeping performance
Kuhlemann and Tierney (2020)	Real coded GA	Minimum FOC	Industrial partner (not specified)	Panamax vessel	Multiple Regions	Over 10% fuel saving
Shin et al. (2020)	Improved A* algorithm	Minimum FOC & ETA	specialized company	Multiple vessels	North Pacific Ocean	Reducing ETA 1.65%
C. Pan et al. (2021)	Improved GA	Minimum FOC	ECMWF	Case ship (S175)	North Pacific	Fuel saving by 7.84%
Wang, Lang and Mao (2021)	Hybrid (Dijkstra, DP and GA)	FOC, GHG emissions ETA	ECMWF and CMEMS	Chemical tanker	North Atlantic	average 5.6% reduction of fuel consumption and GHG emissions
Khan et al. (2022)	GAs	Minimum FOC & voyage time	HYCOM and NOAA	Container ship	3 voyage routes	fuel saving 7.6%, voyage times 8.4% on average
Du, W. et al. (2022a)	Improved three-dimensional dynamic programming	Minimum FOC & ETA	ECMWF	VLCC oil tanker	North Atlantic	fuel saving 1.39% and 1.13% time sailing 4.77% and 5.80%
Grifoll, Borén and Castells-Sanabra (2022)	A* pathfinding algorithm	Minimum sailing time	CMEMS	Ro-Pax vessel	7 voyage routes	18% saved time
Cao et al. (2022)	Improved RRT algorithm	Shortest path with minimum risk	AIS (FigShare platform)	Model ship	Yangtze River (China)	error rates are under 8%, runtime of 1.66 sec.
Moradi et al. (2022)	RL	Minimum FOC & GHG emissions	Stormglass.io	Container ship	Atlantic Ocean	Fuel savings of 6.64%
Ormevik et al. (2023)	Dijkstra algorithm (High-fidelity)	Minimum FOC	Norwegian Meteorological Institute.	Platform Supply Vessel	North Sea	4.5% reduction in fuel consumption
Zhou et al. (2023)	GA and SA	Minimum FOC & voyage time	ECMWF	case ship (S175)	Atlantic Ocean	bypassed the weather warning areas
Gao et al. (2023)	MPFACA	Minimum FOC & GHG	AIS	2 bulk carriers	Yangtze River (China)	Smoother and more efficient route compared to ACO
Liu et al. (2023)	Dijkstra & SPR	Minimum turning points and voyage distance with low risk	Past piracy data	Simulation	3 piracy prone regions	Reduced waypoints 50.54%-62.36%
Zhang, Wen and Tu (2023)	Hybrid (ACO & A-star)	shortest path	AIS	Simulated ship	China Sea	40 nm shorter route and 74.5% reduced turning point
Ha, Roh and Lee (2024)	Improved isochrone method	Minimizing the collision risk	AIS	Simulated ship	Coastal waters	13.6% improvement in average collision risk
Li et al. (2024)	Improved D* Lite algorithm	Multiple optimization	ECMWF & GEBCO	Simulated values	Western Pacific	reduction of 2.32% in distance
Wang et al. (2024)	Hybrid (DRL & Theta-star)	Minimum FOC & GHG	AIS & weather station	Harbor tugs	Singapore port	Up to %74 fuel savings in narrow water
Rafalias (2024)	Hybrid (A-star & NSGA-II)	Minimum FOC & GHG	Sofar Ocean, ECMWF	Multiple vessels	Pacific (200 sensors)	Fuel savings within the range of 5-10%
Chen et al. (2025)	Hybrid (A* & DDQN)	Multiple optimization	CMEMS & AIS	Simulated ship	Mediterranean Sea	11.93 % reduction in fuel consumption and 12.16 % decline in carbon emissions
Chen, Zhang and Fu (2025)	SA and PSO	Minimum GHG (EEOI)	Calculations based on MEPC	Container ship	China Sea (Dalian)	5.85% to 16.93% fuel savings

5. Conclusion

Routing algorithms will be the trend subject in the upcoming years due to the increasing cost of fuel and regulations which force maritime companies to limit their emissions. It is seen that there is still a huge gap between practical applications of such findings at sea and the findings of studies. While studies express their findings about certain amount of fuel, time and distance savings within the limited scenarios, the necessities and needs of real maritime environment is more complex and far from what has been studied. Real maritime environment has a wide range of challenging factors from seasonal weather patterns of each region to waiting period of vessels at anchorage area. It will be important to produce the studies by encompassing realistic factors such as a combination of passage of canals and voyage in high seas, including waiting time at the entrance of straits or ports, negative impact of seasonal adverse weather conditions etc. It is seen in this literature review that, authors of studies regarding routing optimization have to focus on static obstacles, dynamic weather-sea conditions and factors in the maritime environment shaped with realistic conditions.

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Green Maritime Corridors: A Conceptual Perspective Based on Scientific Literature

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Abstract: Reducing greenhouse gas (GHG) emissions is a global objective, and the International Maritime Organization (IMO) continually sets policy measures to facilitate emission reductions in maritime transport. Maritime shipping, although one of the most energy-efficient modes of transport still accounts for a significant share of GHG emissions. In response, new decarbonisation strategies, such as green maritime corridors, are being developed. The aim of this paper is to analyse how the concept is interpreted in recent scientific literature indexed in the Web of Science (WoS) database. A conceptual interpretation was conducted through a literature search and a co-occurrence analysis of titles and abstracts. Annual progress reports on green shipping corridors published since 2022 were further reviewed to examine their implementation in practice. The research shows that green maritime corridors are conceptualised in scientific literature through several interconnected thematic clusters. Furthermore, the analysis shows that the number of green maritime corridor initiatives, together with the involved stakeholders, is rising significantly. Only a small number of initiatives are in the implementation phase, revealing that some barriers remain persistent. This study contributes to an understanding of the relatively new concept and highlights the need to align technological, institutional, and policy dimensions to support its effective implementation.

Keywords: bibliometric analysis; green maritime/shipping corridors; maritime decarbonisation; implementation barriers; stakeholder collaboration

1. Introduction

Since 1997, when the first resolution addressing CO2 emissions was adopted, the IMO has continuously introduced new strategies and measures aimed at reducing GHG emissions from international shipping (International Maritime Organization, 2026a, 2026b). The recently adopted IMO GHG Strategy (2023) sets a target of zero or near-zero net GHG emissions by around 2050 (International Maritime Organization, 2023). Technological innovations and the use of alternative fuels are recognized as crucial elements in achieving this goal (International Maritime Organization, 2026b).

One of the more recent initiatives introduced by the Clydebank Declaration 2021 is the concept of green shipping corridors, defined as zero-emission routes between two or more ports (UK Government, 2021). The Global Maritime Forum defines green shipping corridors as specific routes where technological, economic, and regulatory conditions enable the implementation of zero-emission shipping through coordinated public and private initiatives (Global Maritime Forum, 2022). Such corridors contribute to the decarbonisation of maritime transport by utilising cleaner fuels and advanced technologies not only at sea but also in ports (Garg et al., 2025). Furthermore, they involve multiple stakeholders such as governments, port authorities, shipping companies, logistics operators, and local communities (Garg et al., 2025).

The concept of green maritime corridors has primarily been addressed in policy documents and various international initiatives and has only recently emerged in the scientific literature. The first paper included in this analysis was published in 2023, with a noticeable increase in publications in subsequent years. The literature review by Jugović et al. (2025) indicates that earlier research focused on the role of stakeholders, economic

aspects, and the impacts of policies (Jugović et al., 2025). Although Jugović et al. conducted a bibliometric analysis of green shipping corridors focusing on policy, technology, and stakeholder collaboration relatively recently (March 2025) (Jugović et al., 2025), the number of scientific papers has increased significantly since then. In the analysed dataset, approximately 40% of all scientific papers were published after March 2025. However, it remains unclear how the concept of green maritime corridors is interpreted within scientific literature and how these interpretations relate to practical implementation. Accordingly, this paper aims to analyse how the concept of green maritime corridors is described and interpreted in recent scientific literature indexed in the WoS database using bibliometric analysis. In addition, annual progress reports on green shipping corridors published since 2022 are reviewed to examine the implementation of this concept in practice and to link conceptual interpretation and real-world implementation.

2. Methodology

This study combines bibliometric analysis of scientific literature with a thematic review of industry progress reports in order to bridge the gap between academic theory and industrial practice.

2.1. Literature Search and Dataset Selection

A literature search was conducted in the Web of Science (WoS) Core Collection (Clarivate, n.d.) on February 3rd, 2026. The WoS database was selected for this research because it is recognised as one of the most widely used databases in bibliometric research (Pranckutė, 2021; Li and Wang, 2023). To ensure comprehensive coverage of the topic, a Boolean search string was designed to include variations of the terms "green" and "low-emission" corridors within the maritime domain (Table 1).

Table 1. Literature search strategy in the WoS database

Database	Web of Science Core Collection
Searched field	Topic (Title, Abstract, Keywords, Keywords Plus)
Boolean search string	(“green maritime corridor*” OR “green shipping corridor*” OR “zero-emission corridor*” OR “low-emission corridor*” OR “decarbonized shipping route*”) AND (maritime OR shipping OR port*)
Date of search	February 3rd 2026
Number of records	32

The literature search identified 32 scientific papers, of which one was excluded as it did not address the topic of the green maritime/shipping corridor in the maritime context. The final dataset comprised 31 papers. Despite its relatively small size, it provides an overview of the current state of research in this emerging field and was analysed using the bibliometric workflow illustrated in Figure 1.

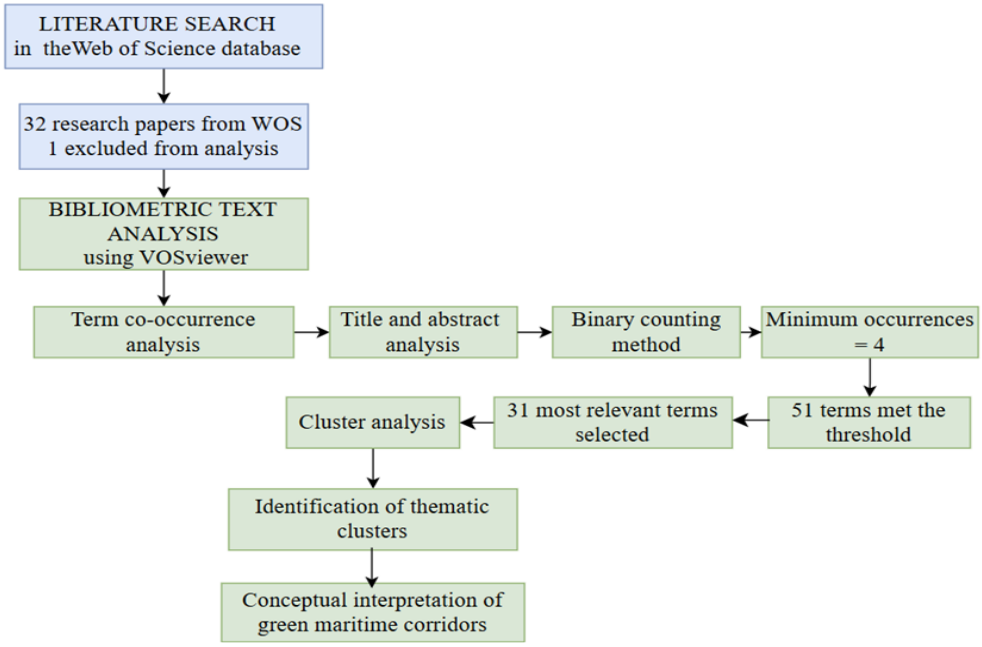


Figure 1. Methodological framework for the literature search and bibliometric analysis.

2.2. Bibliometric and Trend Analysis

Bibliometric analysis is a quantitative method for analysing scientific output and bibliographic data using network analysis and science-mapping techniques. This method enables objective, automated processing of large datasets to identify the structure of the research area, collaborative and interdisciplinary networks, research focuses, and development trends. This analysis is now widely used across various scientific disciplines (Mi et al., 2024). Term co-occurrence analysis of titles and abstracts was conducted using VOSviewer software (van Eck and Waltman, 2009). A binary counting method was applied with a minimum occurrence threshold of four, identifying 51 terms, of which the 31 most relevant were selected for cluster analysis in order to identify the conceptual pillars of the field. To complement the academic perspective, four Annual Progress Reports on Green Shipping Corridors (2022–2025) published by the Global Maritime Forum were analysed (Global Maritime Forum, 2022, 2023, 2024, 2025). This longitudinal analysis enables a comparison between the evolving scientific conceptualisation and the practical milestones achieved in real-world implementation.

3. Scientific interpretation of Green Maritime Corridors

Bibliometric analysis of term co-occurrence produced the results shown in Figure 2, revealing the formation of three clusters, red, green, and blue, within the concept of green maritime corridors. The size of each node represents the frequency of occurrence of a particular term, while the thickness of the lines between two terms indicates the intensity of their interconnection (Figure 2).

The largest red cluster represents emerging decarbonisation concepts and challenges, as the term *decarbonisation* has the highest number of occurrences, followed closely by the term *challenge*. It also includes terms such as *green corridor*, *GHG emission*, *context*, *concept*, and *model*. The term *insight* dominates within the green cluster, followed by *case study*, indicating a focus on implementation-related concepts. The cluster also includes terms related to alternative fuels (*hydrogen*, *ammonia*, and *methanol*), along with the operational aspects such as *vessel* and *voyage*. The smallest blue cluster brings together terms such as *infrastructure*, *adoption*, *IMO*, and the *maritime and shipping industry*, thus connecting the technical infrastructure and regulatory framework needed for green maritime corridors. The results show that the concept of green maritime corridors is described through three connected clusters: decarbonisation, alternative fuels and implementation, and regulatory and infrastructure aspects.

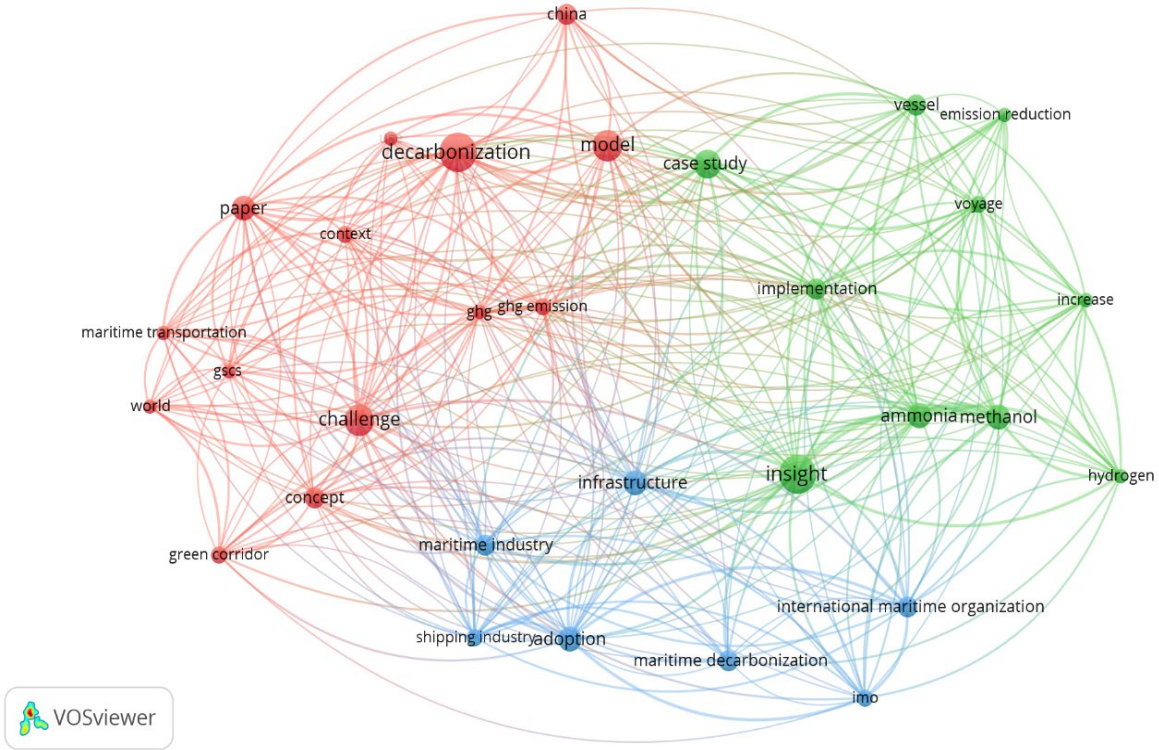


Figure 2. Term co-occurrence network and thematic clusters.

To further examine the correlation between the occurrence of a particular term and its importance within the investigated context, Figure 3 presents the top 10 terms based on co-occurrence, along with their corresponding relevance scores. The results indicate that high co-occurrence does not necessarily imply high relevance scores. Although the term *hydrogen* has low co-occurrence and is only at the chosen threshold, it has the highest relevance score of 2.0, indicating strong conceptual significance. These results suggest that some terms may still be highly important for understanding the concept, despite a lower frequency of occurrence.

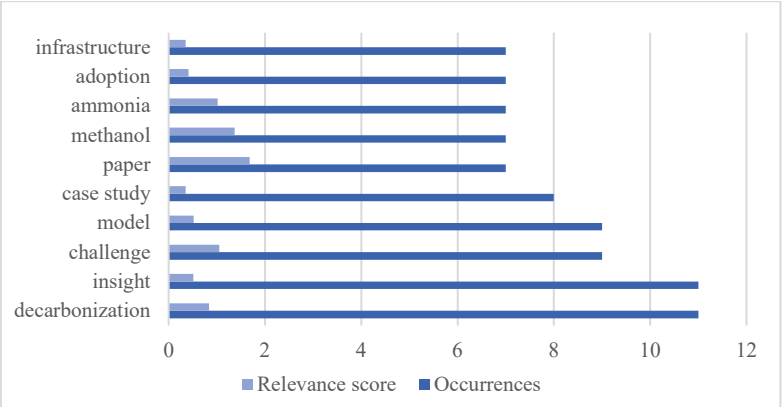


Figure 3. Top 10 terms by occurrence with corresponding relevance score.

4. Implementation of the Green Maritime Corridor over time

Since their introduction, maritime shipping corridors have been developed through a series of steps, each with its own characteristics and challenges. Initially, the concept was organised around three key steps: initiation, planning, and operation. Figure 4 illustrates how this process evolved from 2022 to 2025, with certain activities becoming more defined and progressing from one step to another. In 2023, an additional step, execution including investment decision, was introduced to emphasise implementation. In recent years, the framework has been additionally developed, comprising initiation, exploration, preparation, and realisation. The stages are further divided into distinct sub-steps, highlighting the complexity of the concept and the progression from early planning to full implementation and operation.

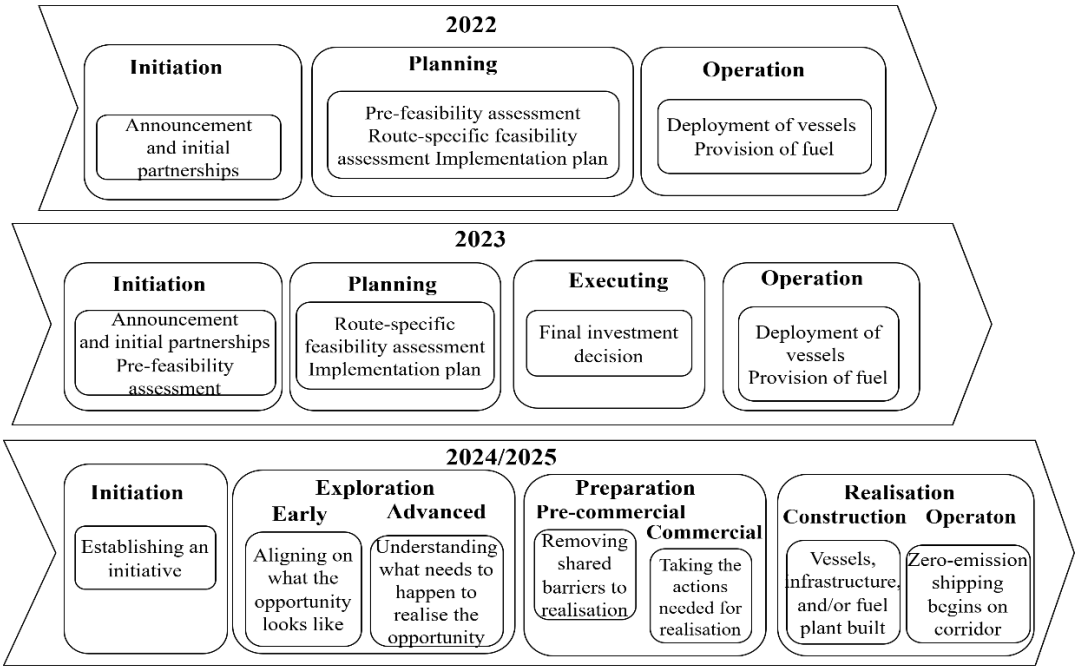


Figure 4. Evolution of the Green Shipping Corridor Development Framework from 2022 to 2025.

By analysing the process over time, an increase in the number of steps and their differentiation during the observed period is evident. Initially, the process involved a simple progression through initiation, planning, and operation. In the following year, a new step was added: the transition from planning to investment decision-making. The most significant development of the framework has occurred in recent years, with more steps and greater specificity. The framework has developed over time, progressing from simpler forms to more advanced steps oriented towards realisation.

The goal of the Clydebank Declaration was to establish at least six green maritime corridors, and, in the first annual report in 2022, this goal was exceeded, with 21 initiatives reported (Global Maritime Forum, 2022). In the following years, continuous growth is noticed, with 44 initiatives in 2023 (Global Maritime Forum, 2023), 62 in 2024 (Global Maritime Forum, 2024), and 84 in 2025 (Global Maritime Forum, 2025). This trend indicates a significant advancement in green maritime corridor initiatives worldwide.

From the initial stage to full implementation, a wide range of stakeholders, including port authorities, vessel owners or operators, fuel producers, classification societies, financial institutions, government, regulators, public and government agencies, researchers, and port operators, play an important role in the development of green maritime corridors. The comparison of annual reports (Global Maritime Forum, 2022, 2023, 2024, 2025) revealed an increase in the number of stakeholders over time, with port authorities remaining the most dominant throughout most of the observed period (Figure 5). In the most recent year, public and government agencies have grown significantly and now form the second-largest stakeholder group. A significant increase in the presence of fuel producers is noted, highlighting their critical importance in enabling alternative fuels. Given that this is a newer concept, the involvement of stakeholders from the fields of knowledge and research is particularly important for addressing all the challenges associated with full implementation. Although each stakeholder has its own role in the implementation of green maritime corridors, changes in stakeholder involvement are evident, indicating a shift from industry actors (vessel owners/operators) to public and governmental actors.

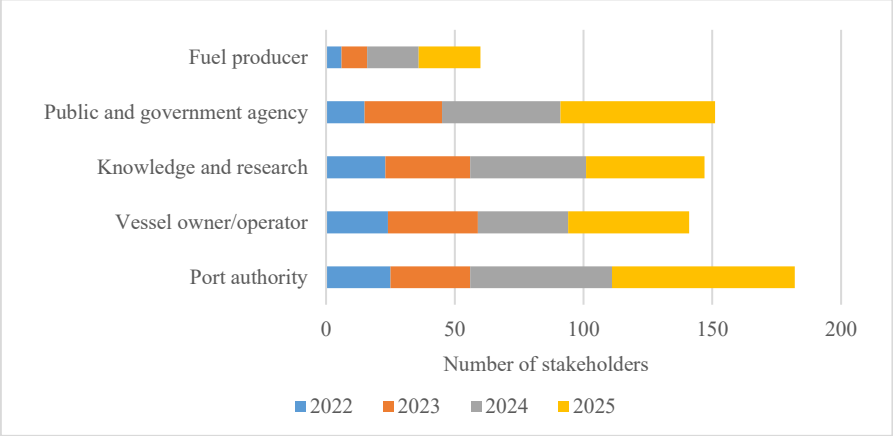


Figure 5. Distribution of key stakeholder groups in green shipping corridor initiatives (2022–2025).

As the concept of a green maritime corridor relies on alternative fuels, it is important to analyse which types of fuels are used or intended for use in these initiatives. Data from the 2022 report were excluded from the analysis because they were calculated differently. Figure 6 shows a clear dominance of methanol across all three years with ammonia also exhibiting a consistently strong presence throughout the observed period. Although methane appeared only in 2024, it increased notably in 2025, together with a strong presence of electric solutions. The results also indicate that initiatives are considering a range of low-emission fuels and are still evaluating whether to adopt a single-fuel pathway or a combination of fuels to address fuel availability constraints. In addition, some initiatives still need to decide which fuel to use, further emphasizing uncertainties in fuel selection.

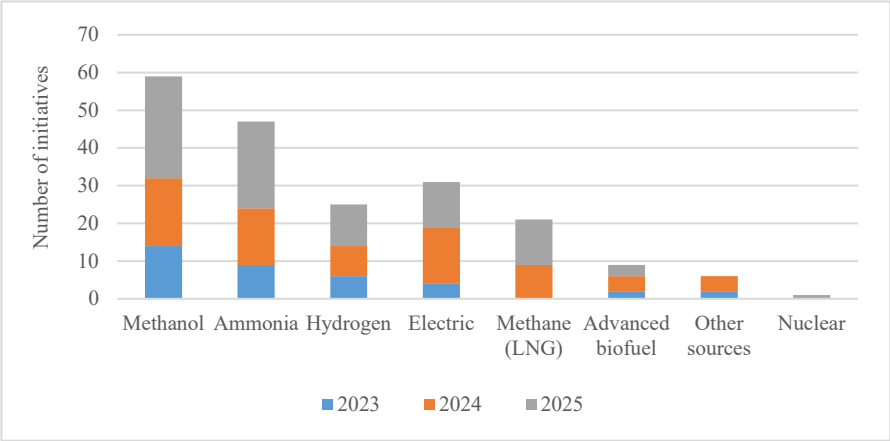


Figure 6. Distribution of fuel types in green shipping corridor initiatives (2023–2025).

5. Discussion and Conclusion

Since the initial initiative to establish the green maritime corridor, various definitions and approaches have emerged during its development, while the decarbonisation process has progressed from the pilot phase to the application phase and stricter regulations (Global Maritime Forum, 2024). The results of the bibliometric analysis show that the concept of green maritime corridors is described in the scientific literature through three interconnected clusters: decarbonisation, alternative fuels and implementation, and regulatory and infrastructure aspects. The bibliometric analysis conducted by Jugović et al. (Jugović et al., 2025), identified four research clusters covering sustainable practices, alternative fuels, green and low-carbon maritime development, and environmental sustainability. These authors had a wider scope of research and a larger data set, which consequently resulted in a larger number of clusters. Comparing the names of the clusters and their roles, the greatest overlap was observed in the alternative fuels cluster. They describe Cluster 2, *Alternative Fuels and Low-Carbon Strategies* as a *comparative evaluation and strategic planning towards decarbonisation through hydrogen, ammonia, and biofuel alternatives* (Jugović et al., 2025). Our green cluster alternative fuels and implementation include various types of alternative fuels, but also emphasise the challenges in fuel selection, as evident in the dominance of the terms insight and case study, highlighting uncertainty regarding the most suitable fuel choice and the need to find appropriate solutions for improvement. Wang et al. highlight the promotion and use of sustainable fuels and technologies as a key objective of green maritime corridors (Wang et al., 2023). Significant investments in infrastructure are required to establish green maritime corridors and support the adoption of alternative fuels, thereby contributing to the national and local economies, as well as to environmental well-being and community interests (Ismail et al., 2024).

Although a large number of green maritime corridor initiatives have been initiated, the latest annual report from 2025 shows that only 4 of these initiatives are in the implementation phase: Australia-East Asia Iron Ore, Oslo-Rotterdam, Stockholm-Turku, Vaasa-Umea. The analysis also shows that a smaller number of initiatives progress to the next phase (Global Maritime Forum, 2025), suggesting that more time is needed or that certain barriers must be overcome. This aligns with the decarbonisation cluster identified in this paper, where the terms decarbonisation and challenges are predominant. The establishment of a green maritime corridor is a complex process and requires effective coordination among different stakeholders, while various barriers limit its successful implementation (Ismail et al., 2024).

Jugović et al. (Jugović et al., 2025) identify the main objectives of green shipping corridors as reducing GHG emissions, fostering stakeholder collaboration, and using low-emission fuels. The concept of green maritime corridors brings together various stakeholders and encourages their joint contribution to reducing GHG emissions (Ismail et al., 2024). A comparison of stakeholders involved in green maritime corridors shows a steady increase in *Knowledge and Research* stakeholders, as they are important in finding solutions for possible barriers.

This growing role of knowledge and research stakeholders, identified in this study, is also recognised within the European Union through efforts to address issues in maritime decarbonisation through research and

innovation projects. One such example is the GREENROUTES project (Project - Green Corridors for Carbon-Neutral Cruise and Ferry Shipping in the ADRION Region, 2026), funded under the Interreg IPA ADRION 2021–2027 programme. The aim of this project is to facilitate the transition of maritime transport towards alternative marine fuels supported by appropriate port infrastructure within the ADRION region. Through its multi-stakeholder approach, involving academic institutions, port authorities, and environmental agencies, the project highlights the role of research and knowledge in addressing key implementation challenges.

In conclusion, the results indicate that, within the analysed literature, the green maritime corridor is conceptualised through interconnected clusters of decarbonisation, alternative fuels and implementation, and regulatory and infrastructure aspects. These findings from the analysed dataset indicate that although the scientific conceptualisation of green maritime corridors is maturing around decarbonisation and infrastructure, full-scale implementation remains limited and challenged by multiple barriers. The analysis further suggests that the next phase of corridor development will depend less on the development of new technologies and more on institutional coordination and knowledge-sharing networks. The identified clusters demonstrate the complexity of the green maritime corridor concept and emphasise that successful implementation relies on the coordinated development and maturity of all related components. This may also explain why only a limited number of initiatives have reached the implementation phase, despite the continual growth in the number of initiatives. Compared with previous bibliometric studies, this research combines bibliometric analysis with an examination of the practical implementation of the green maritime corridor, thus linking conceptual interpretation in scientific literature with real-world implementation. A limitation of this research is the use of a single database, which may have resulted in the exclusion of some publications from the analysis. Future research should focus on socio-economic models that can reduce investment risk for private stakeholders, ensuring that the more than 80 initiatives currently under consideration are successfully converted into operational corridors.

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Conceptual Influence Diagrams as a Learning Method for Understanding Climate Change Impacts on Maritime Transport

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Abstract: Sustainable development in the maritime sector is a complex process and often involves trade-offs. Decision-making is also often siloed by ship, shipowner, logistics company, or government agency. A comprehensive understanding is required in politics, in the drafting of legislation, in business, and when new employees are being trained in their duties or students are training in the field. The conceptual influence diagram method is one approach that makes it possible to visualize complex subject areas and highlight the interactive relationships within a system. In this method, the factors affecting the system are divided into nodes as follows: the chance nodes category includes the factors whose changes are to be examined. Decision nodes contain the factors influenced by chance nodes, and utility nodes represent the system's outcome. The merits of this approach become particularly apparent when examining interrelated issues that, at first glance, appear unrelated. This is especially evident in the context of climate change, where the impacts may be direct or indirect, or resulting from legislation enacted in response to political decisions. This paper reviews the application of the method to the maritime transport sector in the Kymenlaakso region of Finland.

Keywords: influence diagrams, learning method, sustainable maritime transport

1. Introduction

Achieving real sustainability in the maritime sector is a complex objective (Lindstad and Eskeland, 2015; Tatar and Özer, 2018; Trosvik and Brynolf, 2024). It requires an understanding of the diverse environmental impacts of different activities to avoid situations where solving existing problems leads to the creation of new ones. For example, there are various options for reducing greenhouse gas emissions (Aakko-Saksa et al., 2023). However, in some cases emissions may simply be shifted to another stage of the production chain (Chatzinikolaou & Ventikos, 2015). Available technologies, together with their investment and operational costs, play a significant role in ensuring economic sustainability. Changes in economic structures and practices are also necessary to achieve a socio-eco-technically sustainable system.

Due to the complexity of the maritime transport system, stakeholders often approach it based primarily on their own experiences. This silo-based approach may lead to sub-optimization (Uusitalo et al., 2015). One way to mitigate this is the utilization of conceptual influence diagrams (CIDs) as a collaborative learning method to improve the understanding of interactions between entities in complex, interrelated systems (Carriger et al., 2018). This approach can be particularly effective in addressing management problems (Luoma et al., 2021). Conceptual influence diagrams provide a graphical representation of impacts, supporting the consideration of impact mechanisms in decision-making and facilitating stakeholder collaboration by building trust through shared understanding.

Based on the work published by Davies (2011), Kaikkonen et al. (2011), Kinchin et al. (2000), Novak (2010) and Novak & Cañas (2008), causal models and conceptual influence diagrams are often a particularly useful method, especially from a collaborative learning perspective. In this context, "learners" can refer to a large group of people who wish to better understand the impacts of cause-and-effect relationships. For instance, students in the maritime sector require an understanding of the broader context to enhance their overall comprehension, yet this is frequently overshadowed by the fragmentation of course topics. It should be noted

that even those with extensive experience in the field may be unfamiliar with these subjects, as work tasks tend to be highly specialised, and each role typically follows its own unique routine during the workday. Conversely, decision-makers frequently must make decisions with significant consequences and establish policies on matters about which they may only have general knowledge. They must therefore rely heavily on the staff who prepare these matters to support their decision-making.

This paper presents a conceptual influence diagram developed to assess the impacts of climate change on maritime transport in the Kymenlaakso region of Finland (Altarriba, 2025; Pirinen et al., 2012; Tietäväinen et al., 2010). The conceptual influence diagram encompasses both key port operations and vessel traffic. Some elements represent direct consequences of climate-change-driven shifts in prevailing weather conditions and their impact on maritime transport or port operations, including freezing and ice conditions (Merkouriadi & Leppäranta, 2014), wind intensity and sea level fluctuations (Kulikov & Medvedev, 2013), precipitation, heatwaves or foggy conditions (Olsson et al., 2015). However, climate change also gives rise to numerous indirect impacts. For example, these include political pressure to steer stakeholders towards greener solutions through legislation, which has in turn led to the introduction of new fuel and engine technologies (Aakko-Saksa et al., 2023; Kondratenko et al., 2025). Such developments have significant societal implications due to the resulting need for changes in infrastructure. In addition, indirect impacts may also emerge from direct impacts. For instance, wintertime anti-skid measures such as sanding are increasingly required in ports as temperatures fluctuate around the freezing point (Pirinen et al., 2012; Tietäväinen et al., 2010; Veneranta et al., 2016). These measures often lead to severe dust problems during the summer season.

Beyond the previously described application of the conceptual influence diagram method, the objective of this paper is to explore how the method can be employed as a platform for collaborative learning, particularly in the context of stakeholder collaboration. The benefits of computational influence diagrams often emerge in training contexts or stakeholder collaboration, where stakeholders frequently have limited resources to gain a holistic understanding of a system (Novak, 2010; Novak & Cañas, 2008). Without such understanding, sub-optimization can lead to counterproductive outcomes. From a collaborative learning perspective, the emphasis is placed on co-creating the diagram with various stakeholders. This process gives participants valuable experience in the holistic functioning of the system. Once completed, the diagram visually illustrates the system and facilitates discussion on interactions between its components.

2. Conceptual Influence Diagrams as a Collaborative Learning Support Method

Conceptual influence diagrams are a method for modelling causal relationships within systems (Novak, 2010; Novak & Cañas, 2008). This method has been particularly successful in the study of environmental problems, as it is common in such research to have to draw conclusions and generalise based on often incomplete data. Carriger et al. (2018) address this issue using conceptual influence diagrams specifically from the perspective of supporting environmental policy or administrative decision-making. The conceptual influence diagrams consist of chance, decision, and utility nodes, which form an interaction network. The method can be used, as in the application in this paper, to observe causal relationships. However, it can also be extended to a computational influence diagram model, in which different nodes may contain computational algorithms or observational data that can be analysed using, among other methods, Bayesian network computation (Carriger et al., 2021; Uusitalo, 2007). This approach has been applied by Haapasaari et al. (2012), for instance, in their analysis of the Baltic herring fisheries management research problem. Parviainen et al. (2019) have also used this approach to develop risk mapping, identification and management for oil drilling in Arctic regions. Their study concluded that perceptions of oil spill risk were often one-sided or incomplete across different stakeholder perspectives. The study also concluded that progress can be made towards a shared understanding of the risk by utilising social learning and collaborative knowledge production.

This approach has also been applied to the management of invasive species and biofouling on ship hull structures below the waterline (Luoma et al., 2021), which is also a rather complex issue. Fouled hulls increase fuel consumption and thus ships' air emissions, but toxic coatings such as anti-fouling biocides cause contamination of the marine environment and seabed sediments (Luoma et al., 2022). In addition, biofouled hulls can act as a pathway for the spread of invasive species, and aggressive species can, at worst, cause significant environmental impacts as they spread to new areas. Biofouled hulls can be cleaned in-water by scuba divers, if local restrictions allow in-water cleaning. The choice of hull coatings and cleaning method has a significant impact on the cleaning frequency as well as outcomes (Oliveira & Granhag, 2020). Additionally, in

the Baltic Sea, ship coatings must withstand the mechanical stress caused by ice conditions. A conceptual influence diagram is a useful tool that allows one to examine the problem visually and pay particular attention to the system's interactions. A Bayesian network model enabling calculation and optimisation was also developed from this framework (Luoma et al., 2022). However, in such cases, the network often needs to be simplified, as relevant data for calculation procedures may not be available for all nodes. The diagram presented in this paper would likely require further simplification before being translated into a Bayesian model. This is primarily due to the challenges associated with quantifying and statistically linking many of the interactions represented in the model using the currently available data. For example, while the effects of wind-induced sea water level fluctuations on maritime traffic or port operations are relatively easy to represent conceptually, quantifying these relationships remains challenging because the system involves a large number of variables. In this sense, the conceptual approach offers greater freedom to focus on examining the issue specifically at the systemic level.

3. The Conceptual Influence Diagram of the Maritime Sector in Kymenlaakso, Finland

The use of conceptual influence diagrams is often most effective when the method is applied as a tool for collaborative learning in stakeholder engagement processes. Although the resulting diagrams can become graphically complex despite efforts to maintain simplicity, each model nevertheless remains a simplification of a complex reality. As stakeholders often contribute valuable practical insights but may lack access to scientific knowledge and systematically analyzed scientific statistical data, the success of collaborative workshops and discussions depends heavily on the thorough preparation of the researchers facilitating them. The model presented in this paper is based on a literature review, supplemented by expert judgment and stakeholder discussions.

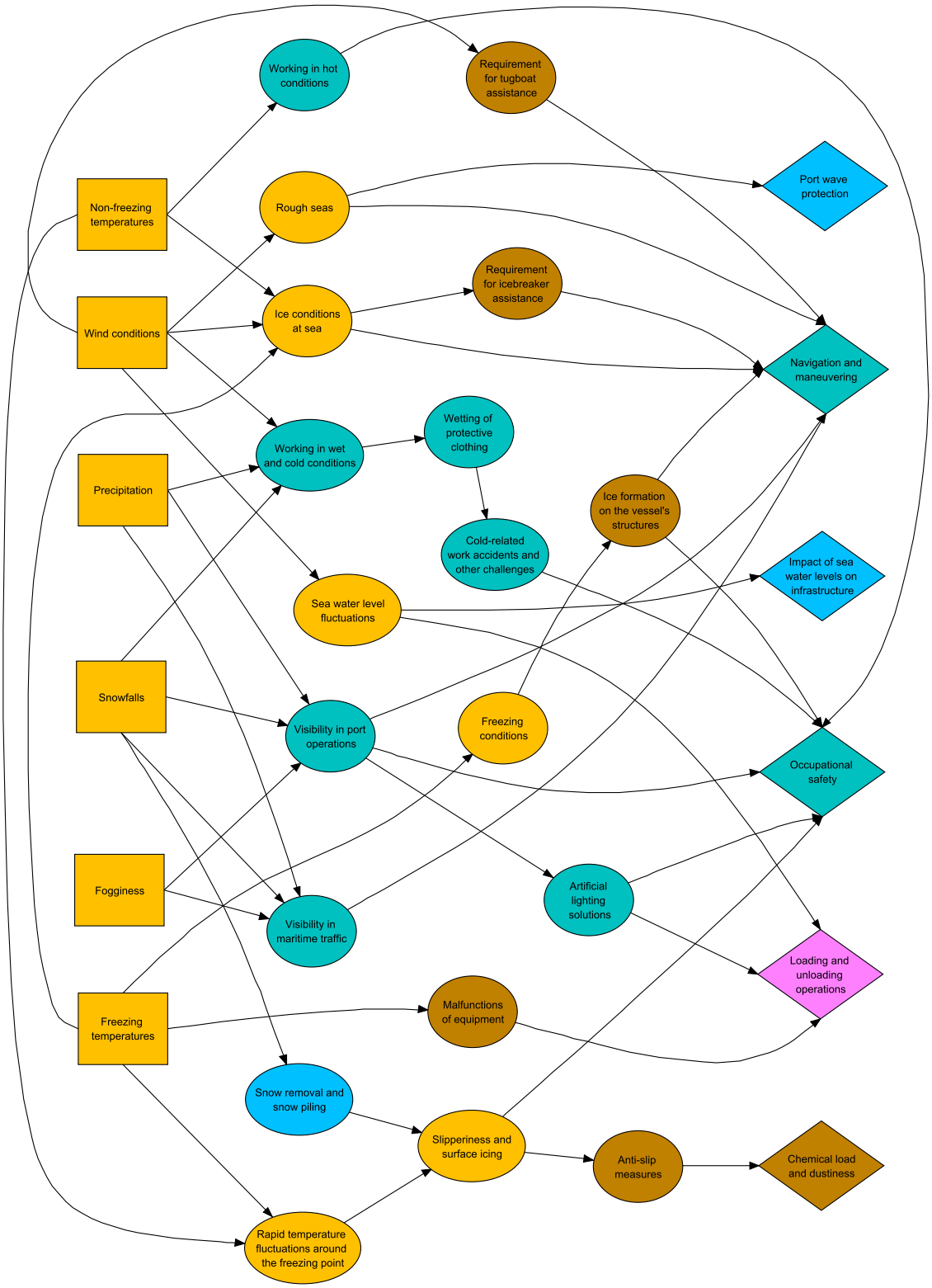
Figure 1 presents a conceptual influence diagram (CID) model, developed to illustrate the effects of weather conditions (Altarriba, 2025; Olsson et al., 2015; Tietäväinen et al., 2010) on the merchant shipping sector in the Kymenlaakso region, on the coast of the Gulf of Finland in southeastern Finland. The purpose of this approach is to examine the potential impacts of climate change on the region's maritime transport sector. Climate change has a direct impact on prevailing weather conditions, which in turn have a significant effect on many operations in the sector. In Figure 1, rectangular change nodes on the left represent weather conditions and regional changes. Diamond-shaped utility nodes are shown on the right, while circular nodes indicate decision points. The system contains both strong, clearly defined interactions and weaker, indirect ones. However, all models are generalisations, and this case is no exception.

In this analysis, the following chance nodes have been selected: freezing and non-freezing temperatures, the wind, precipitation, snowfall, and fog. To capture more detailed interactions, it would be advisable to break these down into subcategories. The utility nodes selected are port wave protection, navigation and manoeuvring, impact of sea levels on infrastructure, work safety, loading and unloading operations, and chemical load and dustiness. In this example, utility nodes that differ significantly from one another have been deliberately selected. Some of these result directly from prevailing conditions, such as the port wave protection node. It should be noted that factors affecting infrastructure already have very broad impacts. The most effective way to prepare for them is through appropriate advanced planning. Furthermore, the impacts on loading and unloading operations are frequent, and the challenges associated with them that arise in this context are well-documented. Dust, on the other hand, is a problem particularly typical of northern ports. Slippery conditions must be combated in winter using sand for de-icing, and it is challenging to remove all the sand from the port yards, even when cleaning is performed regularly. The situation is further complicated by warmer winters resulting from climate change, during which the need for sanding may be intermittent, depending on when there is snow and ice on the ground and when there is not.

Several factors that interact within the system have been represented as decision nodes. As illustrated, non-freezing conditions are denoted by a single chance node. However, as temperatures increase (Olsson et al., 2015; Pirinen et al., 2012; Tietäväinen et al., 2010), particularly during the summer months, this can have a significant impact on port workers, who often work in hot conditions on asphalt surfaces or in machinery. Depending on the type of vessel, it may be easier to protect oneself from the heat while at sea. High wind speeds directly lead to rough seas (Veneranta et al., 2016; Pirinen et al., 2012), and conversely, in winter, both the wind and temperature affect ice conditions at sea (Merkouriadi & Leppäranta, 2014). The wind strength can significantly impact ice movement and accumulation, leading to the formation of pack ice even in areas where

only thin ice is typically present (Vihma & Haapala, 2009). Therefore, thin ice does not necessarily guarantee favourable conditions for shipping. This, combined with the increasing prevalence of energy-efficient EEDI-compliant vessels, is a challenging combination for winter navigation in the future.

Figure 1. Conceptual influence diagram of the Kymenlaakso maritime environment.



Windy conditions present additional challenges. Although the Baltic Sea lacks significant tidal phenomena, wind conditions have a substantial impact on the sea level (Kulikov & Medvedev, 2013). As shown in the data recorded by the Finnish Meteorological Institute's Hamina mareograph (Finnish Meteorological Institute, 2026),

in the Kymenlaakso region, fluctuations in the sea level have reached a range of nearly 3 metres (Altarriba, 2025). These fluctuations have peaked at around 2 metres above average and have fallen to as low as 1 metre below average. Even if the flood limit is not exceeded, high water levels can cause difficulties for loading and unloading operations if the crane reach is no longer sufficient to unload the topmost containers. The ongoing expansion in the dimensions of container ships serves to compound this issue. If the flood limit is exceeded, impacts on coastal infrastructure could be severe, depending on the magnitude of the sea level rise. Conversely, low water levels pose a greater challenge to vessel operations than to port infrastructure. However, available under-keel clearance in port areas and approach channels is relatively limited compared to the requirements of the largest vessels. As a result, loading may not be possible as planned, or vessels may have to wait at anchor for the water levels to rise before entering the port.

Rainy and windy weather can pose significant challenges for individuals working outdoors in port environments. These conditions are set to become more prevalent, as statistics show that the autumn, winter, and spring seasons are warming more than average (Pirinen et al., 2010; Tietäväinen et al., 2010; Veneranta et al., 2016). Rainy weather can cause protective clothing to become wet, while cold and windy conditions can lead to frostbite or colds. Waterproof protective clothing is suitable for heavy rain, but during long periods of drizzle, it can become damp, leading to moisture accumulation inside the clothing due to perspiration. The choice of gloves and their suitability for wet conditions depend on the specific task. In practice, the optimal options are not always available.

Severe frost can cause malfunctions in machinery, and very cold air poses its own challenges. However, appropriate clothing can protect against cold conditions. Once operational, the machines generally function well, except for selective catalytic reduction (SCR) AdBlue systems, which have been found to have inadequate frost resistance. In cold weather, the air is often clear, and wind conditions are typically milder. However, temperature fluctuations (Veneranta et al., 2016) around freezing point can pose significant challenges. Conversely, such conditions, often accompanied by snow or rain, are common in variable weather. This results in snow accumulating on the ground and freezing onto surfaces, forming an extremely slippery layer. Port vehicles may create deep ruts in frozen surfaces. It is essential to address slippery conditions by applying sand. However, this can result in dust generation in ports during the snowmelt season, which is an additional concern that needs to be addressed. Whereas this issue was previously encountered in spring, climate change has led to more frequent cyclical sanding requirements, depending on prevailing winter conditions. It is important to note that sand must be removed regularly during winter to mitigate dust formation. In practice, smooth implementation is not straightforward.

With climate warming, the sea remains open, but icy conditions may become more common. As the sea remains open more frequently while air temperatures are below freezing, spray from waves and moisture in the air can easily freeze onto ship or port structures. In the worst-case scenario, ice accumulation on ship structures can compromise stability, with masses ranging from hundreds to thousands of tonnes depending on the vessel size. In any case, ice on the deck has a detrimental effect on all deck operations and the use of deck equipment. Due to the slippery conditions it creates, there is also a significant occupational safety risk to personnel. In this example, the impact is described in a straightforward manner. However, a more detailed examination of this issue cloud further elucidates the chains of impacts.

An ice-free sea can also cause heavy snowfall directed toward the coast (Olsson et al., 2023). Such events have become more common, particularly along the coastal areas of southern Finland (Olsson et al., 2017). They occur because an unfrozen sea releases large amounts of moisture into the atmosphere, which, upon reaching the cold coast, precipitates as snow. Although there is sufficient snow-clearing equipment and the infrastructure is designed with snowy winters in mind, heavy snowfall often causes numerous disruptions to many societal functions, including port operations. As winters become warmer, periods of mild weather have sometimes followed heavy snowfall, causing the accumulated snow to melt rapidly and leading to winter flooding events.

Weather conditions have both direct and indirect effects on various operations. As shown in Figure 1, the diamond-shaped utility nodes (port wave protection, navigation and manoeuvring, the impact of sea water levels on infrastructure, work safety, loading and unloading operations, and chemical load and dustiness) differ considerably from one another, but the diagram helps to identify chains of impacts and interrelationships. The elements within the impact chains also vary significantly (e.g. requirements for tugboat or icebreaker assistance, wetting of protective clothing, and cold-related occupational accidents). Diagrams can be used to make the analysis more detailed or more general, depending on its objectives. The diagram presented in this paper does

not include alternative fuel solutions, but the same method could also be applied to visualise their effects on the system (e.g. fuel markets, emission fees, bunkering infrastructure, fuel supply security, and spill response actions following accidents), as these effects can be significant even though the change is driven by legislation. Often, climate change is viewed only as a weather-related phenomenon, but its broader effects on society are significant.

4. Conclusions

A conceptual influence diagram is a useful method for clarifying diverse and potentially unexpected chains of interaction and for fostering a comprehensive understanding of the subject under study. The example analysis presented in this paper includes significant impacts at the system level. The diagram examines how non-freezing temperatures, wind conditions, precipitation, snowfall, fog, and freezing temperatures affect the maritime transport sector in Kymenlaakso. These are weather conditions that climate change is particularly likely to influence in the region. Correspondingly, at the other end of the impact chain, the analysis focuses on port wave protection, navigation and manoeuvring, sea levels, occupational safety, loading and unloading conditions, and chemical load and dustiness. The diagram visually illustrates the possible chains of interaction between weather conditions and these factors. Conceptual influence diagrams are particularly useful for developing a holistic understanding of the overall system, where some impacts may be direct and clearly understandable, while others are indirect and potentially unexpected.

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Mapping the Innovation Landscape of Green Technologies in Maritime Transportation: An Integrated Patent Analytics and Forecasting Framework

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Abstract: This paper maps the patent landscape for maritime decarbonisation technologies and assesses the lifecycle stage of each identified technology cluster. The analysis draws on 21,235 patent records published between 2000 and 2024, collected from Lens.org using six domain-specific search queries. BERTopic, an unsupervised topic modelling method based on transformer document embeddings and density-based clustering, identifies 22 technology clusters across six domains: alternative fuels, energy efficiency, electric and hybrid propulsion, hydrogen and fuel cells, wind and renewable energy, and digital compliance. Bibliometric analysis shows that patent activity across all domains remained flat until 2018 and then accelerated sharply, mapping directly onto the IMO Initial GHG Strategy adopted that year. S-curve fitting to cumulative patent counts assesses the commercial development stage of each cluster. Of the 22 clusters, 14 are classified as Emerging. Battery-electric propulsion shows the strongest early-stage commercial momentum in the corpus. Hydrogen propulsion has realised only 12.5% of its estimated carrying capacity. Boil-Off Gas Management moved from near-absent to near-saturated in under five years. The results show a gap between the technologies receiving the most regulatory attention and those where commercial patent investment is actually concentrating.

Keywords: maritime decarbonisation; patent analysis; BERTopic; technology lifecycle; S-curve analysis

1. Introduction

International shipping carries over 80% of world trade by volume and accounts for approximately 2.9% of global greenhouse gas emissions (IMO, 2020). The regulatory pressure to decarbonise the sector has grown substantially since 2018. The IMO 2023 Revised GHG Strategy targets net-zero emissions by or around 2050, with indicative checkpoints of 20 to 30% absolute reductions by 2030 and 70 to 80% by 2040 against a 2008 baseline (Bilgili and Olcer, 2024). The EU Emissions Trading System for maritime and FuelEU Maritime, applicable from 2024 and 2025 respectively, add further compliance pressure for vessels operating in European waters (Du et al., 2025).

The technology pathway to meet these targets is not settled. LNG, methanol, ammonia, hydrogen, wind-assisted propulsion, battery-electric systems, and digital optimisation tools are all under active commercial development at the same time. Laskar et al. (2025), drawing on expert assessments from shipping companies, port authorities, classification societies, engine manufacturers, and investors, find no consensus on a dominant decarbonisation pathway for 2030 or 2050.

Patent intelligence offers a way to read this landscape before commercial deployment makes it visible. Firms file patents before technologies reach market, often by several years, so the patent record captures commercial investment ahead of market signals (Gerken and Moehrle, 2015). Patent-based analyses exist for ship power systems (Sun et al., 2023) and maritime autonomous systems (Belabyad et al., 2025), but none has applied transformer-based topic modelling and lifecycle analysis across the full maritime decarbonisation technology space.

This paper addresses two questions. First, what is the structure of the maritime decarbonisation patent landscape, and how is it organised across technology domains? Second, where do identified technology clusters sit in their commercial development trajectories?

Section 2 reviews the relevant background. Section 3 describes the methodology. Section 4 presents the results. Section 5 discusses the findings and Section 6 concludes.

2. Background and Research Gap

2.1. Regulatory and Technology Context

The IMO 2023 Revised GHG Strategy escalated shipping's decarbonisation target to net-zero by or around 2050 (Bilgili and Olcer, 2024). Zhang et al. (2024) show that reaching the 2030 checkpoint requires alternative fuel penetration in the fleet well beyond the strategy's own projections. The EU ETS Maritime and FuelEU Maritime add a parallel cost layer, with Du et al. (2025) estimating that these instruments make green methanol cost-competitive with conventional bunker fuel by approximately 2035.

On the technology side, Bouman et al. (2017) catalogue over 50 decarbonisation measures with GHG reduction potentials ranging from hull coatings to hydrogen fuel cells. Tomos et al. (2024) find that no alternative fuel can currently deliver full GHG reduction at scale, given production and supply chain constraints. Laskar et al. (2025) confirm that expert consensus on a dominant technology pathway is still absent.

2.2. Patent Intelligence and Landscape Methods

Griliches (1990) establishes patents as a longitudinal, output-oriented, and publicly available record of inventive activity. Because firms file patents before technologies reach commercial deployment, the patent record captures commercial conviction ahead of market signals (Gerken and Moehrle, 2015). The IEA (2021) operationalised this logic for clean energy policy, using patent trajectories to inform government decisions about comparative technology advantage.

For technology landscape mapping, Latent Dirichlet Allocation (LDA) has been widely used but treats documents as bags of words and requires pre-specification of the number of topics. Grootendorst (2022) introduces BERTopic, which generates document embeddings through transformer language models, applies density-based clustering, and extracts topic labels without requiring a pre-set cluster count. George and Sumathy (2023) confirm in direct comparison that BERTopic outperforms LDA on topic coherence and inter-topic distinctiveness. For lifecycle assessment, S-curve fitting to cumulative patent counts is the established method for tracking technology maturity (Andersen, 1999; Belabyad et al., 2025).

2.3. Research Gap

Patent-based analyses of maritime decarbonisation exist but remain narrow in scope. Sun et al. (2023) map ship power system patents from 1965 to 2022. Belabyad et al. (2025) apply patent analysis to maritime autonomous systems. Neither covers the full decarbonisation technology landscape, applies transformer-based topic modelling, or combines landscape mapping with lifecycle assessment across multiple technology domains. This paper fills that gap.

3. Methodology

3.1. Data Collection

Patent data was collected from Lens.org, a publicly accessible database covering over 95% of global patent publications (Lens.org, 2024). Six Boolean search queries targeting technology domains identified in IMO regulatory frameworks and industry classification systems were applied across the B63 CPC classification, which covers ships and related equipment, with a 2000 to 2024 publication window. Table 1 presents the queries and record counts. After removing 6,866 duplicate records using the Lens ID field, the final corpus comprised 21,235 patent records. Fields retained for each record included title, abstract, publication year, kind code, legal status, citation count, simple family size, and CPC classifications.

Table 1. Search queries, technology domains, and record counts.

ID	Search Query (Filter: CPC B63; Years: 2000-2024)	Records
01	(ammonia OR methanol OR hydrogen OR "fuel cell" OR "liquefied natural gas" OR LNG) AND (propulsion OR engine OR fuel OR bunkering OR "dual fuel" OR combustion)	7,795
02	("fuel cell" OR "hydrogen fuel cell" OR "PEM fuel cell" OR "solid oxide fuel cell" OR "battery electric" OR "hybrid electric propulsion" OR "electric propulsion" OR "battery storage" OR "lithium battery" OR "supercapacitor") AND (ship OR vessel OR maritime OR marine OR ferry OR tugboat OR offshore)	4,864
03	("energy efficiency" OR "waste heat recovery" OR "air lubrication" OR "hull optimization" OR "propeller efficiency" OR "shaft generator" OR "heat exchanger" OR "turbocharger" OR "energy saving" OR "EEDI" OR "EEXI" OR "slow steaming" OR "trim optimization" OR "hull form" OR "fouling" OR "air cavity") AND (ship OR vessel OR maritime OR marine)	15,695
04	("wind assisted propulsion" OR "rotor sail" OR "flettner rotor" OR "kite propulsion" OR "wind sail ship" OR "wing sail" OR "wind turbine vessel" OR "solar panel ship" OR "photovoltaic vessel" OR "wind power marine" OR "rigid sail" OR "suction sail" OR "towing kite ship" OR "wind energy ship" OR "renewable energy vessel") AND (ship OR vessel OR maritime OR marine)	982
05	("carbon capture" OR "CO2 capture" OR "carbon dioxide capture" OR "onboard carbon" OR "post combustion capture" OR "exhaust gas treatment" OR "carbon sequestration" OR "CO2 storage ship" OR "amine scrubbing ship" OR "onboard CCS") AND (ship OR vessel OR maritime OR marine)	548
06	("route optimization" OR "voyage optimization" OR "weather routing" OR "ship energy management" OR "emissions monitoring" OR "carbon intensity" OR "CII compliance" OR "SEEMP" OR "digital twin ship" OR "smart ship" OR "predictive maintenance vessel" OR "fuel consumption monitoring" OR "fleet management" OR "port call optimization" OR "just in time arrival") AND (ship OR vessel OR maritime OR marine)	422

3.2. Landscape Mapping via BERTopic

Title and abstract fields were combined to form the input text, following established practice in patent topic modelling (Qiu and Wang, 2022). Document embeddings were generated using the all-mpnet-base-v2 sentence transformer (Reimers and Gurevych, 2019). Dimensionality reduction used UMAP (McInnes et al., 2018) and density-based clustering used HDBSCAN (Campello et al., 2013). HDBSCAN was selected because it does not require a pre-specified number of clusters, handles clusters of irregular shape and density, and explicitly assigns noise points rather than forcing every document into a cluster. Topic labels were extracted using BERTopic's class-based TF-IDF procedure (Grootendorst, 2022), configured with bigram extraction.

3.3. Bibliometric Trend Analysis

Annual patent counts were computed per technology domain and per cluster to track activity over time. Temporal trends were examined against IMO regulatory milestones to assess whether patent activity responds to regulatory signals. The share of patents published after 2020 was computed per cluster as an indicator of recent commercial attention.

3.4. Technology Lifecycle Assessment via S-Curve Fitting

S-curve models fitted to cumulative patent counts per cluster assess each cluster's commercial development stage (Andersen, 1999). Three growth functions were evaluated: the Logistic model, which assumes symmetric sigmoidal growth; the Gompertz model, which allows faster initial growth and a slower approach to saturation; and the Richards model, which adds a shape parameter for asymmetry. Model selection used the Bayesian Information Criterion (BIC), with the Richards model selected only where its BIC score exceeded the best of the other two models by more than six points.

Hold-out temporal validation was applied by fitting each model on data from 2000 to 2019 and evaluating predictive accuracy on the held-out period 2020 to 2024, using Mean Absolute Percentage Error (MAPE). Models with MAPE at or below 10% were classified as High validation confidence, between 10% and 25% as Moderate, and above 25% as Low confidence. Clusters with fewer than 50 patents published before 2020 were classified as N/A for hold-out testing.

Each cluster was assigned to one of five lifecycle stages based on its position relative to the model's estimated carrying capacity at the end of 2024, following the thresholds established by Andersen (1999) and applied in Belabyad et al. (2025): Pre-emergence (fewer than 50 patents or insufficient fitting history), Emerging (below 15% of estimated capacity, or left of inflection point), Growing (15% to 60% of capacity, past inflection point), Maturing (60% to 90% of capacity), and Mature (above 90% of capacity).

4. Results

4.1. Patent Landscape

BERTopic identified 22 technology clusters across six domains. Of the 21,235 records in the corpus, 8,774 were assigned to named clusters. The remaining 12,461 records were assigned to the noise cluster and excluded from cluster-level analysis. Table 2 presents the full taxonomy.

Table 2. Maritime decarbonisation technology taxonomy, 22 clusters.

ID	Domain	Cluster Label	Patents	Median Year	% Post-2020
A1	Alternative Fuels	LNG & Methanol Dual-Fuel Systems	674	2016	28.2%
A2	Alternative Fuels	Ammonia Propulsion & Fuel Supply	236	2016	36.4%
A3	Alternative Fuels	Boil-Off Gas Management & Reliquefaction	262	2023	98.1%
A4	Alternative Fuels	LNG Regasification & Bunkering Infrastructure	583	2018	41.9%
A5	Alternative Fuels	Floating Gas Production & Energy Infrastructure	1,007	2020	50.8%
B1	Energy Efficiency	Exhaust Gas Cleaning & SOx/NOx Abatement	781	2017	34.7%
B2	Energy Efficiency	Waste Heat Recovery & Thermal Energy Cascading	662	2017	39.1%

B3	Energy Efficiency	Air Lubrication & Hull Drag Reduction	331	2018	36.3%
B4	Energy Efficiency	Hull Coatings & Biofouling Control	188	2016	27.7%
B5	Energy Efficiency	Hull Maintenance Robotics & Underwater Inspection	244	2018	43.4%
B6	Energy Efficiency	Shaft Power Generation & Onboard Energy Recovery	178	2019	36.5%
B7	Energy Efficiency	Energy-Saving Hydrodynamic Appendages	106	2022	80.2%
C1	Electric & Hybrid	Battery Electric Propulsion Systems	166	2021	66.3%
C2	Electric & Hybrid	Battery Charging Infrastructure & Shore Power	253	2020	57.3%
C3	Electric & Hybrid	Marine Hybrid Electric Drive Systems	255	2021	67.5%
C4	Electric & Hybrid	Shipboard DC Power Distribution & Grid Architecture	267	2020	51.3%
C5	Electric & Hybrid	Variable-Pitch Propellers & Advanced Propulsor Design	89	2018	31.5%
D1	Hydrogen & Fuel Cells	Hydrogen Propulsion & Fuel Cell Systems	158	2024	84.8%
E1	Wind & Renewable	Wind-Assisted Propulsion: Rotors, Sails & Kites	196	2016	22.4%
E2	Wind & Renewable	Onboard Solar, Wave & Renewable Energy Integration	1,203	2018	39.7%
F1	Digital & Compliance	Voyage Optimisation & Fleet Energy Management	569	2019	48.7%
F2	Digital & Compliance	Carbon Intensity Monitoring & CII/EEXI Compliance	366	2020	62.6%
		Total	8,774		

Note: Patent counts refer to deduplicated records assigned to each cluster by the BERTopic/HDBSCAN pipeline. The total of 8,774 reflects classified patents; 12,461 records were assigned to the noise cluster and excluded from cluster-level analysis.

Alternative Fuels accounts for 2,762 patents, or 31.5% of the classified corpus. Energy Efficiency accounts for 2,490 patents, or 28.4%. Together these two domains represent nearly 60% of all classified activity. By contrast, Hydrogen and Fuel Cell Systems accounts for just 158 patents, or 1.8% of the classified corpus.

4.2. Bibliometric Trends

As shown in Figure 1, patent activity across all six domains remained relatively flat between 2000 and 2017. Activity then accelerated sharply from 2018, mapping directly onto the IMO Initial GHG Strategy adopted at MEPC 72 in April 2018. By 2023, annual classified patent counts had more than doubled relative to the 2015 to 2017 baseline. Across the full corpus, 40.6% of all patents were published in the five-year window from 2020 to 2024, compared to 5.1% in the equivalent window from 2000 to 2004.

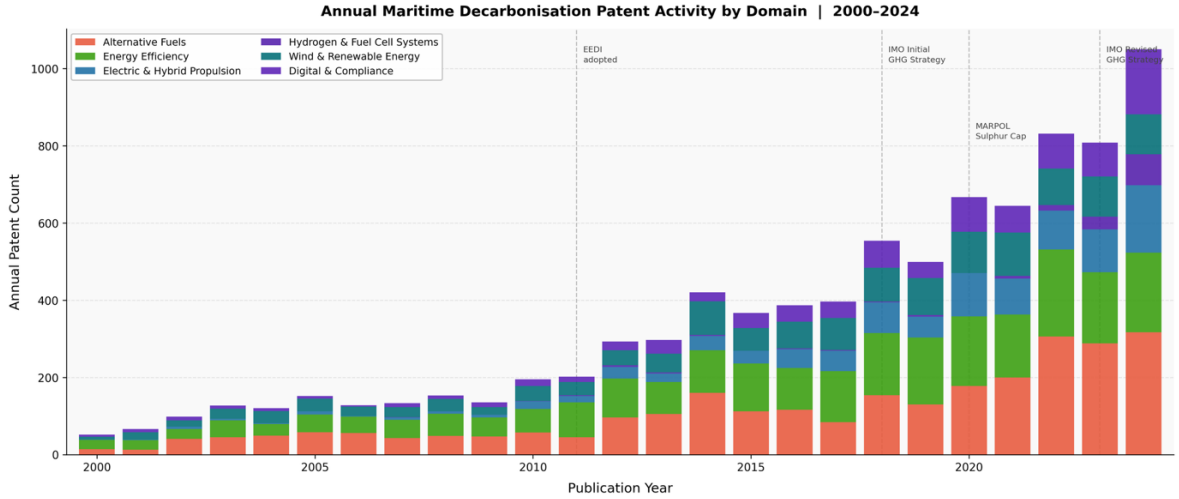


Figure 1. Annual patent activity 2000 to 2024 by domain with IMO regulatory milestone annotations.

4.3. Technology Lifecycle Trajectories

Table 3 presents the lifecycle classifications and S-curve validation results for all 22 clusters. Of the 22 clusters, 14 are classified as Emerging, five as Maturing, two as Growing, and one as Mature. The majority of maritime decarbonisation technology clusters have not yet passed their patent activity inflection point.

Table 3. S-curve lifecycle classifications for all 22 clusters.

ID	Cluster Label	Model	Stage	% K (2024)	Validation
A1	LNG & Methanol Dual-Fuel	Gompertz	Growing	46.4%	High
A2	Ammonia Propulsion	Gompertz	Emerging	29.3%	Moderate
A3	Boil-Off Gas Management	Logistic	Maturing	86.4%	N/A*
A4	LNG Regasification	Logistic	Emerging	33.2%	High
A5	Floating Gas Production	Logistic	Emerging	39.4%	Moderate
B1	Exhaust Gas Cleaning	Gompertz	Emerging	26.8%	High
B2	Waste Heat Recovery	Gompertz	Emerging	32.1%	Moderate
B3	Air Lubrication	Richards	Maturing	85.8%	High
B4	Hull Coatings	Gompertz	Mature	97.4%	High
B5	Hull Maintenance Robotics	Logistic	Emerging	32.8%	Moderate
B6	Shaft Power Generation	Logistic	Maturing	75.4%	Moderate
B7	Hydrodynamic Appendages	Logistic	Emerging	15.7%	N/A*
C1	Battery Electric Propulsion	Logistic	Emerging	36.4%	Low
C2	Battery Charging & Shore Power	Logistic	Emerging	29.1%	Moderate
C3	Marine Hybrid Electric Drive	Logistic	Emerging	30.8%	Low

C4	Shipboard DC Power	Gompertz	Emerging	24.9%	Moderate
C5	Variable-Pitch Propellers	Logistic	Maturing	83.6%	Low
D1	Hydrogen & Fuel Cells	Logistic	Emerging	12.5%	N/A*
E1	Wind-Assisted Propulsion	Logistic	Maturing	86.6%	High
E2	Solar, Wave & Renewable	Logistic	Emerging	48.8%	High
F1	Voyage Optimisation	Logistic	Emerging	33.1%	High
F2	CII/EEXI Compliance	Logistic	Growing	51.3%	High

Note: % K (2024) is the percentage of estimated carrying capacity realised at end of 2024. Validation confidence is based on hold-out MAPE for 2020 to 2024: High (MAPE at or below 10%), Moderate (10% to 25%), Low (above 25%). *N/A indicates insufficient pre-2020 patent history for hold-out testing; lifecycle classification for these clusters is indicative.

The most notable case is Boil-Off Gas Management and Reliquefaction (A3). This cluster has 98.1% of its patents published after 2020 and its cumulative count has already reached 86.4% of its estimated carrying capacity. It moved from near-absent to near-saturated in under five years. This compression tracks directly to the LNG vessel ordering wave from 2018: as those vessels entered commercial service from 2021, the engineering challenge of managing boil-off gas became commercially urgent very quickly.

At the other end, Hydrogen Propulsion and Fuel Cell Systems (D1) has realised only 12.5% of its estimated carrying capacity. Its median publication year is 2024 and 84.8% of its patents appeared after 2020. Its inflection point is not yet visible in the data. Battery Electric Propulsion (C1) remains Emerging but shows a projected inflection point around 2026, the earliest in the Electric and Hybrid domain.

5. Discussion

The patent landscape shows that commercial R&D attention in maritime decarbonisation concentrates heavily in Alternative Fuels and Energy Efficiency, which together account for nearly 60% of all classified patents. LNG and methanol dual-fuel systems carry the largest single-cluster patent count and are classified as Growing. Hydrogen, the fuel most prominently featured in regulatory strategy documents, accounts for less than 2% of the classified corpus and sits firmly in the Emerging stage with no inflection point yet in sight.

The lifecycle picture shows that maritime decarbonisation is not nearing commercial resolution. Fourteen of 22 clusters are still Emerging. This finding is consistent with Laskar et al. (2025), who find no expert consensus on a dominant fuel pathway for 2030 or 2050. The patent record adds a firm-level evidence layer: commercial actors have not yet concentrated strongly enough in most technology clusters to push them past their inflection points.

The Boil-Off Gas Management case shows how quickly this picture can change. A cluster that barely existed in 2019 had nearly saturated its estimated carrying capacity by 2024. Coccia and Roshani (2024) find that technology lifecycle durations are compressing across domains. The BOG result is driven by a specific commercial trigger: the delivery of LNG vessels ordered from 2018. For any institution with a multi-year preparedness pipeline, this case illustrates the risk of monitoring technologies reactively rather than tracking patent trajectories in advance.

6. Conclusion

This paper applies BERTopic and S-curve analysis to 21,235 maritime decarbonisation patents published between 2000 and 2024. The analysis identifies 22 technology clusters, maps their distribution across six domains, and assesses the lifecycle stage of each cluster.

Three findings stand out. Patent activity across all domains accelerated sharply from 2018, directly following the IMO Initial GHG Strategy. Of the 22 clusters, 14 remain Emerging, showing that most maritime decarbonisation technologies are still in early commercial development. The Boil-Off Gas Management cluster compressed from near-absent to near-saturated in under five years, demonstrating that commercial consolidation can outpace institutional response timelines.

The methods used here are replicable and can be updated as new patent data becomes available. Future work will extend the analysis by incorporating patent quality indicators and regulatory timeline mapping to produce a sequenced institutional preparedness output applicable to shipowners, classification societies, port authorities, and investors.

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Developing and Validating an ESG-Oriented MET Framework for Safe and Green Ship Recycling

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Abstract: Ship recycling is a major environmental, social and governance challenge in maritime transport because environmental risk, worker safety, documentary control and accountability converge at the end-of-life phase of ships. Following the entry into force of the Hong Kong Convention, safe and green recycling depends not only on yard facilities but also on the competence of maritime professionals who interpret evidence, manage risks and verify claims. This paper develops and validates a maritime education and training framework for ship recycling, using India as the primary policy context and the Hong Kong Convention as the normative reference. The study combines a systematic evidence review, doctrinal regulatory analysis, systems-theoretic risk reasoning, expert interviews, a two-round Delphi validation, scenario-based usability testing and analytic hierarchy process prioritisation. The results identify seven environmental, social and governance critical control points and seven competency domains, all of which exceeded Delphi validity thresholds. Prioritisation ranked hazardous-material and environmental-risk management, data governance and digital evidence management, and regulatory literacy as the highest implementation priorities. Early pilot results indicate improved case-analysis performance, but are interpreted as preliminary implementation evidence rather than proof of long-term organisational impact. The framework offers a traceable pathway from regulatory obligation to role-based competency, learning outcome and assessment design for ship-recycling education and professional upskilling.

Keywords: maritime education and training; environmental, social and governance; ship recycling; Hong Kong Convention; competency framework; safe and green recycling

1. Introduction

Ship recycling is one of the most contested sustainability issues in maritime transport. It generates economic and circular-economy benefits through material recovery, yet it can also create hazardous waste, worker injury, weak documentation and enforcement problems when controls fail (ElMenshawy, Ülkü and Hsuan, 2024; Koilo, 2025). These problems are not isolated technical defects. They arise at the intersection of environmental protection, labour safety, evidence management and institutional accountability.

This paper treats ship recycling as an Environmental, Social and Governance (ESG) challenge and Maritime Education and Training (MET) as part of the implementation infrastructure for safe and green recycling. The Hong Kong International Convention for the Safe and Environmentally Sound Recycling of Ships, hereafter the Hong Kong Convention, entered into force on 26 June 2025 and has sharpened the need for professionals who can manage inventories of hazardous materials, ship-specific recycling plans, facility authorisation, worker safety, environmentally sound waste handling, certification and reporting (International Maritime Organization, 2009, 2025).

India is a major ship-recycling jurisdiction and has adopted a domestic legislative framework through the Recycling of Ships Act 2019 and the Recycling of Ships Rules 2021. It therefore provides a policy-relevant context for examining how ESG expectations can be translated into MET design (Mannan, Rizvi and Dai, 2024; Mathew, 2024). The study uses India as the primary policy context while treating the Hong Kong Convention as the normative reference for international relevance.

The central gap is not the absence of research on ship recycling, regulation or sustainability. Rather, existing studies rarely provide a traceable pathway from regulatory obligation and socio-technical risk to role-based competency, measurable learning outcome and validated assessment logic. Regulatory analysis explains

what must be controlled, and sustainability literature explains why these controls matter, but MET scholarship still lacks a validated framework that translates these demands into assessable professional capability.

Accordingly, this paper addresses three research questions: (1) which post-Hong Kong Convention ESG obligations and socio-technical risks generate competency needs in ship recycling; (2) which competency domains are judged valid, necessary and implementable by experts; and (3) which domains should be prioritised for early curriculum implementation. The contribution is therefore deliberately bounded: it is not a claim that no ESG-related training exists, but that a validated and traceable MET framework for ship-recycling ESG governance remains underdeveloped.

2. Literature and Regulatory Background

2.1 Ship recycling as an ESG governance issue

Recent literature shows that ship recycling can no longer be treated merely as an operational dismantling activity. Systematic reviews have identified environmental burdens from hazardous materials, social risks associated with worker safety and informal work practices, and governance challenges related to authorisation, traceability and accountability (ElMenshawy, Ülkü and Hsuan, 2024; Hadjiyianni and Pouikli, 2024; da Silveira et al., 2025). Circular-economy studies add a complementary perspective by emphasising material recovery, secondary markets and sustainability-oriented business models (Agarwala, 2023; Scipioni, Dini and Niccolini, 2023; Tola et al., 2023).

The ESG lens is useful because it connects these streams instead of treating them as separate domains. The environmental dimension concerns pollution prevention, hazardous-material control and waste management. The social dimension concerns worker health, competence, human factors and emergency preparedness. The governance dimension concerns authorisation, documentary integrity, traceability, escalation logic and assurance against misleading sustainability claims. In ship recycling these dimensions are interdependent: a documentary failure can become an environmental failure, a weak permit-to-work decision can become a worker-safety failure, and an unsupported ESG claim can mask both.

2.2 Regulatory developments and the post-Hong Kong Convention environment

The Hong Kong Convention provides the primary normative reference for this study. Its requirements cover the Inventory of Hazardous Materials, ship-specific recycling planning, authorisation of recycling facilities, worker protection, environmentally sound management of hazardous materials and reporting obligations (International Maritime Organization, 2009). India's Recycling of Ships Act 2019 and Recycling of Ships Rules 2021 further illustrate how Convention-related obligations are operationalised within a major recycling jurisdiction (Mannan, Rizvi and Dai, 2024; Mathew, 2024). The European Union Ship Recycling Regulation is used only as a limited benchmark for traceability, documentary control and assurance expectations, not as a full comparative legal analysis (Hadjiyianni and Pouikli, 2024).

The regulatory literature is therefore necessary but not sufficient for MET design. Regulations specify duties and controls, but they do not automatically define the professional capabilities required to interpret inventories, recognise unsafe control conditions, challenge inadequate evidence or make defensible escalation decisions under operational pressure.

2.3 Competence-based maritime education and existing frameworks

The educational foundation of the framework draws on competence-based education, constructive alignment and sustainability-competence scholarship. Competence is understood as the integrated ability to mobilise knowledge, skills, judgement and responsibility in context, rather than as the possession of isolated factual knowledge (Mulder, 2014). Constructive alignment requires learning outcomes, teaching activities and assessment tasks to be explicitly connected (Biggs and Tang, 2011). Sustainability-competence literature similarly emphasises systems thinking, anticipatory judgement, normative reasoning and strategic action (Wiek, Withycombe and Redman, 2011).

Existing MET competency frameworks and model courses remain essential for seafarer safety, operational competence and regulatory familiarity. However, they are not designed specifically for post-Hong Kong Convention ship-recycling workflows, nor do they usually connect ESG assurance, hazardous-material traceability, documentary evidence and anti-greenwashing judgement to role-based learning outcomes. The

proposed framework therefore improves on general MET and ESG education approaches by linking specific ship-recycling obligations to competency domains, evidence-based assessment and implementation priorities.

2.4 Conceptual contribution

The conceptual contribution is a governance-oriented competence model. The framework positions ESG not as a descriptive checklist of three pillars but as a control problem in which professionals must maintain safe, lawful and verifiable recycling processes across multiple handovers. A competency was retained only when it had normative anchoring, meaning a direct link to a legal, regulatory or recognised assurance requirement; theoretical anchoring, meaning support in competence or sustainability-education theory; socio-technical criticality, meaning relevance to an unsafe control condition or material ESG failure; and pedagogical assessability, meaning that the competence could be translated into observable learning outcomes and assessment criteria.

3. Methodology

3.1 Study design and method integration

The study adopted a pragmatic sequential multi-method design informed by design-science research. The object of the study was an educational artefact: an ESG-oriented MET framework that had to be grounded in evidence, consistent with regulatory obligations, meaningful to practitioners and assessable in training contexts (Hevner et al., 2004; Peffers et al., 2007). The design was question-driven rather than method-driven. Each method had a defined function in the chain from evidence to validated curriculum design, as summarised in Table 1.

Table 1. Methodological integration and quality-control logic.

Stage	Method	Function in the study	Quality-control logic
Evidence base	PRISMA-guided review	Identify ship-recycling, ESG, competence and educational-design evidence	Database search, citation chaining, screening criteria and extraction frame
Normative basis	Doctrinal and directed-content analysis	Translate legal and policy duties into actors, decisions, documents and implied competences	Traceability matrix linking obligations to competencies
Risk logic	Systems-Theoretic Process Analysis reasoning	Identify unsafe control conditions and ESG-critical control points	Retention only where competence was linked to material losses
Practice refinement	Expert interviews	Test completeness, wording and contextual feasibility	Maximum-variation sampling and structured thematic analysis
Content validation	Two-round modified Delphi	Test relevance, clarity, necessity and implementability	Content validity, median, interquartile range and revision between rounds
Usability testing	Scenario focus group	Stress-test use of the framework in realistic ship-recycling decisions	Four scenarios covering evidence, safety, waste and assurance failures
Prioritisation	Analytic hierarchy process	Rank implementation priorities for curriculum roll-out	Pairwise comparisons, geometric aggregation and consistency checks

3.2 Evidence review and regulatory analysis

The evidence review followed the logic of the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) statement while recognising that the study also included selected policy and guidance sources relevant to regulatory implementation (Page et al., 2021). Searches were conducted in Scopus, Web of Science Core Collection and education resources information center, supplemented by backward and forward citation chaining. The review covered 2009–2025 and included peer-reviewed articles, review papers, books or book chapters, and policy or guidance documents relevant to ship-recycling governance, ESG, competence requirements and educational design.

Two reviewers independently screened titles and abstracts before full-text eligibility assessment. Disagreements were resolved by discussion. Extraction used a coding frame covering source type, jurisdiction, ESG pillar, stakeholder role, ship-recycling workflow, digital or documentary control, competence implication and educational-design implication. The PRISMA-guided flow is reported in Figure 1.

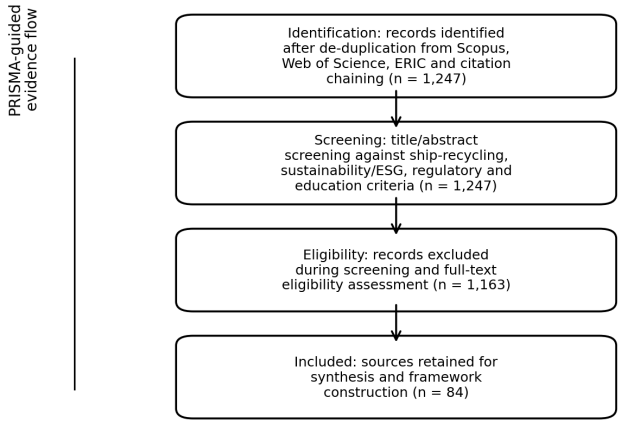


Figure 1. PRISMA-guided evidence flow for source identification, screening and inclusion.

Doctrinal and directed-content analysis was then applied to the Hong Kong Convention, India's Recycling of Ships Act 2019 and Recycling of Ships Rules 2021, relevant implementation guidance and selected elements of the European Union Ship Recycling Regulation. Legal and procedural requirements were coded by ESG pillar, obligated actor, decision point, documentary or evidentiary demand and implied competence. This produced a regulatory competency traceability matrix that formed the normative backbone of the framework.

3.3 Framework construction

Framework construction followed design-science logic and Systems-Theoretic Process Analysis (STPA)-informed socio-technical reasoning. An ESG-critical control point was defined as a recurrent decision, handover or verification moment at which inadequate competence could produce a material environmental, social or governance failure. Four unacceptable losses structured the analysis: severe worker injury or fatality, toxic release or uncontrolled hazardous-material exposure, unverifiable or misleading compliance or ESG claims, and breakdown of material or waste traceability.

Candidate competencies were retained only when they showed normative anchoring, theoretical anchoring, socio-technical criticality and pedagogical assessability. Retained competencies were translated into intended learning outcomes, learning activities and assessment logic using constructive alignment and outcome-based education principles. Figure 2 summarises the framework-development pathway from evidence synthesis to validation and prioritisation.

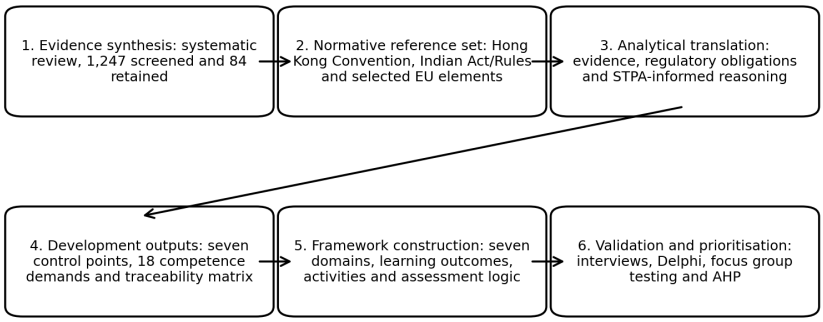


Figure 2. Framework-development pathway for the ESG-oriented ship-recycling MET framework.

3.4 Empirical validation and prioritisation

Ethical approval for the human-participant components of the study was obtained from AASTMT under approval code AASTMT/CMTT/65/2026. Participation in interviews, Delphi rounds, focus group activities and pilot feedback collection was voluntary; informed consent was obtained from all participants; and identifying information was removed during analysis and reporting.

Framework refinement began with semi-structured interviews with 21 experts recruited through purposive maximum-variation sampling across six stakeholder groups: regulators, ship-recycling yard managers, health, safety and environment or compliance officers, classification or survey professionals, waste-management specialists and MET academics. The interview protocol covered five areas: participant role and experience, recurring compliance or safety failures, competence gaps, digital and documentary evidence needs, and feasibility of implementation. Interviews were conducted online between June and August 2025 and were analysed in NVivo 14 using structured thematic analysis, with a subset double-coded.

The revised framework was then evaluated through a two-round modified Delphi process involving 17 panellists selected for depth of expertise rather than statistical representativeness. Eligibility required at least five years of direct experience or equivalent research expertise in ship recycling, maritime regulation, health and safety, classification or survey work, waste management, ESG assurance or MET. Panellists rated competency statements, modules and assessment components for relevance, clarity, necessity and implementability using a five-point scale. Consensus was assessed using item-level Content Validity Index (I-CVI), scale-level average Content Validity Index (S-CVI/Ave), Lawshe's Content Validity Ratio (CVR), median and interquartile range. Items not meeting thresholds were revised and returned in Round 2.

A structured focus group was used for usability testing. Four scenarios were used: discrepancies in the Inventory of Hazardous Materials (IHM), hot-work authorisation under operational pressure, traceability failures in hazardous-waste handling, and unsubstantiated ESG assurance claims. The session was used to refine rubric wording, escalation triggers and evidence-handling prompts.

Finally, the retained domains were prioritised using the Analytic Hierarchy Process (AHP). The AHP instrument was administered to the expert panel after Delphi validation. Pairwise comparisons were structured around four criteria: regulatory criticality, ESG materiality, socio-technical risk severity and pedagogic urgency. Judgements were aggregated using the geometric mean. For each competency domain, the ESG Competency Priority Index was calculated as ESG Competency Priority Index (ECPI)

$$ECPI_i = \sum_{j=1}^{m} w_j \cdot s_{ij}$$

where w_j denotes the weight assigned to the criterion j and s_{ij} denotes the normalised score of the competency domain i under the criterion j. Consistency ratios below 0.10 were treated as acceptable, and a one-way sensitivity analysis was used to test the robustness of rank order under moderate variation in criterion weights.

4. Results

4.1 Framework development outputs

The PRISMA-guided search identified 1,247 post-deduplication records. Screening and eligibility assessment retained 84 sources directly relevant to ESG, ship recycling and MET. Evidence from the retained sources was combined with regulatory analysis and STPA-informed reasoning to identify 18 recurring competence demands across seven ESG-critical control points: IHM verification, facility authorisation, ship recycling planning, worker safety, waste traceability, ESG claim verification and stakeholder coordination. The main development outputs are shown in Table 2.

Table 2. Framework development outputs.

Output category	Number	Main result
Records identified after de-duplication	1,247	Scholarly and policy sources screened
Sources retained	84	Direct relevance to ESG, ship recycling and MET
ESG-critical control points	7	IHM, facility authorisation, ship recycling planning, worker safety, waste traceability, ESG assurance and coordination
Recurring competence demands	18	Synthesised from evidence review, regulatory coding and STPA-informed reasoning
Preliminary competency domains	7	Initial framework architecture for validation

4.2 Validation outcomes

The expert interviews confirmed the relevance of the preliminary framework to post-Hong Kong Convention compliance and ESG assurance challenges. They also led to clearer wording and three additional sub-competencies covering IHM interpretation, contractor oversight and escalation logic.

The two-round Delphi process validated all seven competency domains. Domain-level I-CVI values ranged from 0.82 to 1.00, median scores ranged from 4 to 5, interquartile range values ranged from 0 to 1, and CVR values ranged from 0.65 to 1.00. The overall S-CVI/Ave was 0.91, indicating good content validity. Regulatory literacy and compliance assurance received the highest support, while circularity, resource recovery and sustainability reporting received the lowest support, although it remained above the retention threshold. Round 2 results are reported in Table 3.

Table 3. Delphi validation results for competency domains, Round 2 (n = 17).

Competency domain	I-CVI	Median	IQR	CVR	Retained
Regulatory literacy and compliance assurance	1.00	5	0	1.00	Yes
Hazardous-material and environmental-risk management	0.94	5	1	0.88	Yes
Labour safety, human factors and emergency preparedness	0.94	5	1	0.88	Yes
Data governance, document control and digital evidence management	0.88	4	1	0.76	Yes
Ethical assurance and anti-greenwashing judgement	0.88	4	1	0.76	Yes
Circularity, resource recovery and sustainability reporting	0.82	4	1	0.65	Yes
Stakeholder coordination, communication and escalation	0.94	5	1	0.88	Yes

4.3 AHP prioritisation and framework structure

The AHP criterion weights were regulatory criticality (0.38), ESG materiality (0.27), socio-technical risk severity (0.22) and pedagogic urgency (0.13). The highest-priority domains were hazardous-material and environmental-risk management, data governance and digital evidence management, and regulatory literacy and compliance assurance. One-way sensitivity analysis varying criterion weights by ±20% showed that the top three domains remained stable, indicating robustness at the upper end of the ranking. The prioritisation results are shown in Table 4, and the validated framework structure is shown in Table 5.

Table 4. ESG Competency Priority Index (ECPI) scores and ranking.

Competency domain	ECPI score	Rank
Hazardous-material and environmental-risk management	0.213	1
Data governance, document control and digital evidence management	0.187	2
Regulatory literacy and compliance assurance	0.161	3
Labour safety, human factors and emergency preparedness	0.152	4
Ethical assurance and anti-greenwashing judgement	0.112	5
Stakeholder coordination, communication and escalation	0.098	6
Circularity, resource recovery and sustainability reporting	0.077	7

Table 5. Validated framework structure.

Module	Title	Selected learning outcome
1	ESG governance and assurance in ship recycling	Evaluate ESG implications of ship-recycling decisions
2	Hong Kong Convention, Indian regulation and documentary compliance	Interpret IHM and Ship Recycling Facility Plan requirements
3	Hazardous materials, waste control and environmental protection	Evaluate waste traceability systems
4	Labour safety, human factors and emergency response	Conduct permit-to-work risk assessment
5	Digital evidence, traceability and anti-greenwashing controls	Audit evidence supporting ESG claims
6	Circularity, material recovery and sustainability reporting	Prepare a verifiable sustainability disclosure
Capstone	Integrated decision simulation	Apply competencies in a realistic time-pressured scenario

4.4 Early pilot evaluation

An initial pilot implementation was conducted with 28 Indian maritime professionals between October and December 2025. At Level 1 (Reaction), the mean satisfaction rating was 4.6/5.0 and 96% of participants agreed that the content was relevant to their role. At Level 2 (Learning), mean rubric-based case-analysis scores improved by 37% from pre- to post-intervention assessment (paired-samples t-test, $p < 0.001$). These findings

are interpreted as early-stage implementation evidence only. Level 3 (Behaviour) evaluation remains in progress, and Level 4 (Results) evaluation is planned through longitudinal tracking of facility audit outcomes.

Table 6. Pilot evaluation summary.

Evaluation level	Measure	Result
Level 1 (Reaction)	Mean satisfaction rating	4.6/5.0
Level 1 (Reaction)	Participants agreeing content was relevant to their role	96%
Level 2 (Learning)	Pre-/post-improvement in case-analysis performance	37%
Level 2 (Learning)	Statistical significance	$p < 0.001$
Level 3 (Behaviour)	Follow-up evaluation status	In progress
Level 4 (Results)	Organisational impact evaluation status	Planned

5. Discussion

This study contributes to ship-recycling scholarship and MET practice by repositioning safe and green ship recycling as a competence-intensive ESG governance challenge. The results show that hazardous-material control, documentary integrity and governance-oriented judgement are mutually reinforcing components of sound recycling practice rather than separate training topics.

The first contribution is theoretical and conceptual. By combining competence-based education, constructive alignment, sustainability competencies and ESG governance, the framework explains why ship-recycling education should extend beyond technical awareness. Professionals must be able to interpret regulatory obligations, recognise unsafe control conditions, evaluate evidence and make defensible escalation decisions. This addresses the reviewer-relevant concern that ESG should not be treated descriptively. In the revised framework, ESG is operationalised as a set of interdependent controls that can fail if professional judgement, evidence and accountability are weak.

The second contribution is methodological. The sequential design avoids treating multiple methods as an accumulation of rigour. Instead, the review identifies evidence, regulatory analysis establishes the normative backbone, STPA-informed reasoning links obligations to losses and control points, interviews refine the artefact for practice, Delphi testing validates content, scenario testing examines usability, and AHP prioritises implementation. This integration is important because curriculum design for ship recycling must be simultaneously regulatory, socio-technical and pedagogical.

The third contribution is practical. Existing MET and ESG education approaches offer important foundations, but they rarely provide a ship-recycling-specific pathway from obligation to competency, learning outcome and assessment. The proposed framework therefore supports curriculum development, professional upskilling and scenario-based assessment in maritime institutions, regulatory training environments and industry-facing programmes.

The findings also indicate implementation challenges. Competencies related to digital evidence, traceability and anti-greenwashing assurance are highly relevant, but they may be difficult to implement in resource-constrained or partially digitised training settings. The India-centred design strengthens contextual relevance, but transfer to other jurisdictions will require adaptation to local law, labour conditions, institutional capacity and digital maturity. The pilot findings are promising, yet they remain limited to reaction and short-term learning outcomes; they do not yet demonstrate behavioural transfer or organisational impact.

6. Conclusions

This paper developed and validated an ESG-oriented MET framework for safe and green ship recycling, using India as the primary policy context and the Hong Kong Convention as the normative reference. It addresses a specific gap in current scholarship by providing a traceable progression from regulatory obligation and socio-technical risk to role-based competency, learning outcome and implementation priority.

The framework was constructed through a systematic evidence review, doctrinal regulatory analysis, STPA-informed reasoning, expert interviews, a two-round Delphi process, scenario-based usability testing and AHP prioritisation. Seven competency domains were validated, with hazardous-material and environmental-risk management, data governance and digital evidence management, and regulatory literacy emerging as the highest-priority implementation areas.

The study demonstrates that ship recycling is not only a facility-governed compliance issue. It is also a competence-governed ESG assurance issue in which environmental, social and governance outcomes depend on professional judgement, documentary integrity, traceability and accountable decision-making. The framework can therefore support curricula, short courses, simulation-supported learning and professional development in ship-recycling education.

Several limitations remain. The validation process was expert-based and does not yet prove long-term behavioural or organisational impact. The pilot provides early evidence of implementation but not sustained transfer to workplace performance. In addition, the India-centred design requires adaptation before broader application in other ship-recycling jurisdictions. Future work should test behavioural transfer, evaluate organisational outcomes, compare implementation across jurisdictions and refine digital evidence modules for different levels of institutional capacity.

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Toward Safety-Centred Training Models for Alternative Fuel Ships: Human-Factors Analysis and GMP-BoK Based Guidelines for Maritime Education and Training

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Abstract: As the maritime industry embraces alternative marine fuels, the complexity of operational systems introduces many challenges, including increased toxicity, increased fire risk, greater challenges for rapid emergency response, and heightened operational hazards. Although improved technological system design can mitigate risks, the human-performance dimension has not matured correspondingly and remains the weak link in alternative-fuel operations and Maritime Education and Training (MET). This paper describes the human factors involved in preparing seafarers for alternative-fuel operations and translates them into guidelines for a safety-centred design training model. A qualitative, framework-based, multi-method research design applied. This includes structured literature synthesis and hazard-human interaction analysis within bunkering, routine operations, and emergency response situations; Human Factors Analysis and Classification System (HFACS)-type grid construction; and competence mapping against the Global Maritime Professional Body of Knowledge (GMP-BoK). The analysis revealed four recurring categories of challenges: cognitive load and alarm complexity; psychosocial pressure and risk perception in high-stakes situations; skill gaps associated with new fuels, automation, and interfaces; and organisational and curriculum constraints. The author aligned these categories with the specified GMP-BoK competence areas, including technological literacy, situational awareness, decision-making, risk management under uncertainty, leadership, and resilience. A safety-centred training logic for alternative-fuel operations that goes beyond conventional minimum-competence standards is necessary, and the author provides guidelines that suggest a course with many options.

Keywords: Human Factor; Alternative Fuels; Maritime Education and Training: MET; GMP-BoK

1 Introduction

Decarbonisation of shipping is no longer a long-term hope; it is now an operational necessity. The International Maritime Organisation (IMO) has recently updated its 2023 Strategy on the reduction of Greenhouse Gas (GHG) Emissions from Ships. This means international shipping aims to eliminate net GHG emissions to mitigate climate change, while increasing the adoption of near-zero-GHG fuels and energy sources during the transition to 2050 and beyond (IMO, 2023). The maritime workforce is therefore required to adapt to new fuels and energy systems with a wide range of theatrical and emergency profiles that differ from those that shaped traditional training regimes. Maritime Education and Training (MET) will need to evolve rapidly to ensure new energy systems are sufficiently safe and operational.

As primary stakeholders in the shipping industry, ship crews will begin adopting new fuel systems with limited knowledge of the systems in use and will mitigate unfamiliar risks. Primarily, ammonia (respiratory risks), methane (low flash point and high fire risk), and hydrogen (uncontrollable and highly flammable) will be present in fully operational digital control environments. Along with increased operational complexity, hybrid systems will incorporate automated control structures and require a higher level of integrated, highly cross-functional coordination from the bridge, engine, and shore-side teams. This configuration will have highly alarmed automated control structures (Ismail et al., 2024; Ismail, Metwalli, and Alamoush, 2025). The shipping industry has recognised and agreed that the transition to low/zero-carbon fuels will require significant additional training in all operational, technical, and ancillary fields of training, ship system awareness, and all levels of decision-making, control, and coordination systems (DNV, 2022; WMU, 2023; Lloyd's Register Foundation, 2024)

Hence, the focus is on strategic training. International law regarding MET sets universal minimum standards for maritime competence, represented in the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), and embedded into national law by member states' signatures. This law's framework is focused on maintaining minimum requirements. On the other hand, the International Association of Maritime Universities (IAMU) has developed the Global Maritime Professional Body of Knowledge (GMP-BoK) as an outcome-based and internationally customisable educational model. The GMP-BoK goes beyond the minimum certification requirements and integrates academic, soft, and future skills (IAMU, 2019, 2026).

This paper addresses the following question: What should form the safety foundation of training models for alternative-fuel ships? Its contribution is twofold. First, it identifies recurring human-factor challenges that span key alternative-fuel operating scenarios. Second, it translates those challenges into a safety-centred set of curriculum design guidelines anchored in the GMP-BoK. The novelty of the paper lies in integrating structured evidence synthesis, scenario-based operational analysis, HFACS-informed organisation of contributory factors, and competence mapping into an educational framework. Rather than proposing a narrow syllabus for a single institution, the paper develops an analytically grounded design logic that can be adapted across MET institutions, training centres, shipping companies and administrations.

2 Literature Review

2.1 Alternative fuels, operational risk and the human element

The rapid policy and market shift toward alternative fuels is creating a new safety landscape. Official IMO guidance recognises that the use of alternative fuels brings associated risks that require dedicated familiarisation, basic and advanced training, with the generic interim guidelines establishing an international reference point for training development and approval (IMO, 2025a). The same IMO programme notes that fuel-specific interim guidelines for methanol, ammonia, hydrogen, LPG, battery-powered ships and fuel cells are being developed in parallel with the comprehensive STCW review, and the IMO Sub-Committee on Human Element, Training and Watchkeeping (HTW) 12 has already finalised interim guidelines for methyl/ethyl alcohols and ammonia as fuel (IMO, 2026).

Industry and academic reports converge on the view that decarbonisation is not only a fuel-substitution problem. DNV (2022) identifies higher-skilled seafarers, stronger safety capabilities, and upskilling for digital and automated operations as direct consequences of the decarbonisation pathway. Similarly, World Maritime University (WMU)'s Transport 2040 report concludes that technology will not eliminate the need for seafarers but will alter the skill mix demanded of them, particularly regarding automation, digitalisation, and complex socio-technical work (WMU, 2023). Recent maritime human factors studies reinforce this point by demonstrating the roles of alarm interpretation, situational awareness, trust in automation, and cognitive workload in determining safe performance in highly mediated operational environments (Chan et al., 2022; Nizar, Miwa and Uchida, 2024).

2.2 Why STCW alone is not enough

The STCW Convention remains the global regulatory baseline for training, certification and watchkeeping. Its core purpose is to ensure that seafarers are qualified and fit for duty from the standpoint of safety of life, property, and environmental protection (IMO, 2017). This minimum-standard logic remains essential. However, it is not designed, by itself, as a full curriculum architecture for emerging fuel ecosystems characterised by interface complexity, alarm overload, uncertainty, and high-consequence operational deviations.

The current transition period makes this limitation more visible. IMO acknowledges that the comprehensive review of the STCW Convention and Code has entered a critical revision phase, with more than 400 gaps identified, many of which are linked to innovation, the energy transition, and seafarer well-being (IMO, 2026). The need for interim generic and fuel-specific training guidelines confirms that existing minimum requirements are insufficient to structure the knowledge, skills and behaviours required for alternative-fuel operations (IMO, 2025a, 2025b). This confirms that existing minimum requirements are necessary but insufficient for designing coherent knowledge, skills, and behavioural outcomes for alternative-fuel operations.

Table 1. STCW and GMP-Bok compared as foundations for alternative fuel training design

Dimension	STCW baseline	GMP-BoK Contribution	Implication for alternative fuel safety
Regulatory role	Minimum global standard for certification and watchkeeping	Outcome-based educational guide for curriculum and course design	Training design must go beyond compliance while remaining STCW-consistent
Competence depth	Strong on baseline safety and duty qualification	Adds higher-order cognitive, affective, and psychomotor outcomes	Supports decision quality, resilience, and socio-technical readiness
Response to innovation	Under comprehensive review, interim guidance is now needed	Explicitly revised for technology, sustainability, and new MET approaches	Better suited to emerging fuel systems and future-oriented MET
Curriculum tools	Does not provide a complete course-design architecture	Provides Focus Areas (FAs)[1], Color Coding Concept Tables (CCCTs)[2], and prerequisite logic	Enables systematic translation of risk into training outcomes
Safety emphasis	Safety is foundational but generic	Safety can be operationalised through multiple competence areas	Supports fuel-specific, scenario-based, and multi-domain safety learning

As shown in Table 1, STCW remains necessary but not sufficient. The transition to alternative fuels requires a training logic that can organise advanced human performance demands into coherent learning outcomes, delivery methods, and assessment strategies. That is precisely where GMP-BoK adds value.

3 Methodology

3.1 Study design and methodological rationale

This study adopts a qualitative, framework-building design intended to move from dispersed evidence on alternative-fuel operations to a transferable safety-centred training logic. The design is neither a meta-analysis nor a purely descriptive narrative review. Instead, it combines structured literature synthesis, operational scenario analysis, HFACS-informed classification, and competence mapping to the GMP-BoK to derive curriculum-design guidelines. This choice is appropriate because the research objective is not to measure the effect of a single intervention, but to integrate heterogeneous evidence into a conceptually coherent design framework.

This approach is rooted in the logic of structured, conceptually oriented reviews, which are helpful when a field is emerging and yet too immature for fine-grained effect-size aggregation or a single-variable synthesis. (Snyder, 2019; Jaakkola, 2020). A protocol-driven systematic review would not be particularly appropriate, as the relevant literature includes technical guidance, human factors studies, simulator-based education research, policy documents, and safety studies related to specific fuels and lacks common outcome measures. Similarly, an empirical simulation study would identify performance issues in a particular context. However, it would not provide the answer to how a training system should be structured across different fuels, institutions, and regulatory frameworks.

3.2 Source identification and selection

Source selection criteria were based on steps of identification, screening, and inclusion. Priority was given to peer-reviewed studies, IMO publications, acknowledged industry reports and authoritative institutional literature published between 2020 and 2026 All selections were retained according to their relevance to (1) alternative marine fuels and operational risk; (2) maritime human factors and human-automation interaction;

[1] A Focus Area (FA) is a key area of competence (including knowledge, skills, and abilities) needed by Global Maritime Professionals (GMPs) to perform well in their jobs. A FA consists of some combination of knowledge and information, attitudes and values, skills, and abilities across all domains of learning. (IAMU,2026)

[2] The CCCTs are used in the second version of the GMP-BoK to simplify its use and implementation for users and reduce the number of tables from 18 in the first version to three tables in the second version. This concept allows users to view all the ILOs across the four tiers in a single table for each domain, with each tier assigned its own color code. (IAMU, 2026)

(3) simulator-based MET, competence design, and assessment; and (4) regulatory and educational frameworks relevant to training design, especially STCW, IMO interim guidance, and GMP-BoK.

Sources were located using academic databases and search engines relevant to maritime and transport research, as well as from the direct acquisition of official documents from recognised relevant organisations. The search included combinations of the following terms: alternative fuel ship training,' ammonia bunkering safety,' methanol human factors,' maritime alarm management,' maritime automation workload,' simulator-based maritime training,' HFACS maritime,' STCW alternative fuels,' and 'GMP-BoK.' Sources were retained if they provided analytical input on at least one of the following: operational risks; recurring human-factor scenarios; training or competency issues; and educational/regulatory design aspects. Duplicates as well as sources that were unsubstantiated, overly promotional, or only loosely relevant were excluded.

3.3 Scenario construction and hazard–human interaction analysis

The study presents three representative operational scenarios: bunkering, routine operation, and emergency response. These scenarios were deliberately selected because they exemplify the most consequential phases through which practicable competence in alternative fuels is expressed. Bunkering focuses on transfer-related risk, coordination-related burden, and exposure to the direct consequences of errors; routine operation involves human interaction with automation, alarm systems, and supervision in a degraded state, while emergency response shows how, under uncertainty, time pressure, and increased danger, crews are affected. For each scenario, the analysis examined how human operators interact with technical systems, work procedures, and organisational conditions. The objective was not to reconstruct a single accident sequence, but to identify recurrent performance pressures and breakdown mechanisms that appeared across the literature. These recurrent pressures were then abstracted into cross-scenario human-factor challenge categories.

3.4 HFACS-informed classification

The Human Factors Analysis and Classification System (HFACS) was used as an organising lens rather than as a stand-alone accident investigation method. This choice is defensible because HFACS has been widely applied and adapted in safety research to structure the interaction of active and latent factors across unsafe acts, preconditions, supervision, and organisational influences (Hulme et al., 2019). In the present study, HFACS helped prevent the analysis from collapsing alternative-fuel risk into operator error alone. Instead, it enabled the study to organise challenge categories across multiple layers of the socio-technical system, including interface design, alarm environments, team interaction, supervision, curriculum architecture and institutional readiness.

3.5 GMP-BoK mapping and guideline synthesis

Once recurring challenge categories had been identified and organised, they were mapped to relevant GMP-BoK competence FAs. The purpose of the mapping was not to force a one-to-one correspondence between every challenge and a single isolated competence item, but to determine which combinations of technical, cognitive, affective, psychomotor, and organisational capabilities were necessary for safe performance. This mapping process then informed the derivation of eight safety-centred guidelines that move from analytical diagnosis to training-design implications.

4 Findings

Analysing the three operational scenarios of bunkering, routine operation, and emergency response identified human-factor challenges that affected safety and the performance of operational tasks. The analysis revealed four recurring human-factor challenge categories that consistently influenced safe performance, although their specific manifestations varied by context. During bunkering, these challenges manifested primarily as high cognitive workload, coordination demands, unfamiliar fuel-transfer systems, and the immediate pressure of high-consequence errors (DNV, 2022; Duong et al., 2023). In routine operation, operational challenges included interpreting alarms, supervising automated systems, reduced familiarity with systems when they behaved abnormally, and the risk of complacency when things seemed under control (Chan

et al., 2022; Nizar, Miwa and Uchida, 2024). During emergency response, the intensity of operational challenges was affected by time pressure, uncertainty, the rapid need for communication and clarity of roles, and the need to take technically correct actions (DNV, 2022; IMO, 2025b).

The human-factor challenges were categorised systematically, from scenario-specific observations to higher-order categories defined by their mechanisms. In the context of bunkering operations, high cognitive demand, given the multitude of signals and coordination, was classified as cognitive workload and alarm complexity. In contrast, ignorance regarding fuel transfer systems was classified as a skill barrier to understanding new fuel systems and their interfaces. Being under pressure from high-consequence errors was classified as pressure, stress, and high-consequence risk perception. In the context of routine operations, monitoring and interpreting alarms from an automated system were also classified as cognitive workload and alarm complexity. Similarly, unfamiliarity with a system's abnormal behaviour was classified as a skill barrier to understanding new fuel systems and their interfaces. Complacency in stable conditions was described as impaired risk perception and was classified under pressure, stress, and high-consequence risk perception. During emergency response, under time pressure and in rapid decision-making, stress and high-consequence risk perception were identified. Role ambiguity and communication breakdowns were attributed to organisational and curricular limitations, as well as design inadequacies in training and teamwork.

Table 2. Human-factor challenge categories and their GMP-BoK alignment

Challenge category	How it appears in operations	HFACS level(s)	Relevant GMP-BoK FAs
Cognitive workload and alarm complexity	Multiple alarms, weak signals, unfamiliar escalation pathways during bunkering, and abnormal operations	Unsafe acts; preconditions	Technological literacy, situational awareness, and decision-making
Skill gaps in new fuel systems and interfaces	Low familiarity with fuel-system logic, sensors, automation, and control interfaces	Unsafe acts; preconditions; supervision	Technical competence; technological literacy; problem solving
Stress and risk perception under high consequence	Toxicity, flammability, and emergency stakes amplify stress, hesitation, and communication breakdowns	Preconditions: unsafe supervision	Adaptability and resilience; emotional intelligence; leadership
Organisational and curriculum limitations	Generic training, weak prerequisite design, poor update mechanisms, and limited scenario realism	Unsafe supervision; organisational influences	Capacity for lifelong learning, academic research, professional and ethical responsibility

The absence of a single technical module cannot explain the reasons in Table 2. Challenge categories span individual cognition, operational context, supervision, and organisational design. This is also why a safety-centred training model for alternative-fuel ships needs to be multi-domain and multi-level rather than just procedural.

5 Results: Safety-Centred Guidelines for Any Training Model for Alternative-Fuel Ships

The core result of this study is a set of guidelines that can serve as the foundation of any training model for alternative-fuel ships. The focus is deliberately on safety. These guidelines are not proposed as a fixed course template; rather, they are design principles that can be adapted by MET while remaining aligned with the logic of GMP-BoK and the current IMO transition agenda.

Table 3. Safety-centred guidelines to underpin alternative-fuel ship training models.

Guideline	Safety Rationale	GMP-BoK FAs	Implication for Training Design
1. Use safety as the organising principle	Training should be structured around the protection of life, environment, and assets rather than fuel familiarisation alone.	Technical competence, professional and ethical responsibility, and sustainability	Design outcomes, scenarios, and assessments around safe performance under normal and abnormal conditions.

2. Build training around representative scenarios	Alternative-fuel competence is context-dependent and emerges in bunkering, monitoring, and emergencies.	Situational awareness, decision making, problem solving	Use scenario sets that mirror fuel transfer, system supervision, containment failures, and escalation events.
3. Make emergency preparedness fuel-specific	Generic emergency drills do not capture toxicity, cryogenics, dispersion, ignition, or isolation differences across fuels.	Risk management under uncertainty; technical competence; adaptability and resilience	Develop drills and simulations for fuel-specific leak, fire, toxic exposure, and shutdown situations.
4. Treat alarm management and interface use as safety topics	Automation can increase, not reduce, cognitive burden when interfaces are unfamiliar or alarm logic is poorly understood.	Technological literacy, situational awareness, and decision-making	Train seafarers to interpret, prioritise and act on alarms under time pressure and uncertainty.
5. Integrate communication, leadership, and emotional regulation	High-consequence operations fail when teams fragment, hesitate, or communicate poorly under stress.	Leadership, interpersonal communication, emotional intelligence, collaboration, and teamwork	Assess communication discipline, shared situational awareness, and calm command behaviour during scenarios.
6. Use multi-domain competence assessment	Written tests alone cannot demonstrate readiness for alternative-fuel operations.	Cognitive, affective, and psychomotor domains across relevant FAs	Combine knowledge testing, simulator performance, behavioral observation, and structured debriefing.
7. Design progressive prerequisites and refresher pathways	Alternative-fuel training should build on earlier competence and remain up to date as technology and regulation evolve.	Capacity for lifelong learning; prerequisite concept; Action Verb Taxonomy (AVT)[3] and CCCTs	Use staged entry requirements, refresher modules, and modular updating for new fuels and systems.
8. Support implementation with instructor readiness and review loops	Training quality depends on instructors, institutional feedback, and continuous updating.	Academic research; capacity for lifelong learning; peer-assisted implementation logic	Establish train-the-trainer preparation, feedback capture, and periodic course review tied to regulatory change.

Table 3 is the principal contribution of the study. The table shows that a future training model for alternative-fuel ships should begin with safety architecture rather than content accumulation. Guideline 1 establishes safety as the organising principle because alternative-fuel operations can fail catastrophically when training is designed around system familiarisation rather than around decision quality, hazard recognition, and protective action. Guidelines 2 through 5 translate this principle into pedagogic structure: scenario realism, fuel specificity, alarm and interface competence, and team-based control of stress and communication. Together, these rows reposition safety as a competence system rather than a checklist.

The second half of the Table addresses implementation quality. Guidelines 6 to 8 make clear that safety-centred training will remain weak if it is assessed only through written examinations, detached from prerequisite logic, or delivered by instructors who are not themselves prepared for rapidly changing fuel and technology contexts. These findings closely mirror the implementation emphasis of GMP-BoK, which was revised not only to update FA but also to simplify course design and institutional uptake through action verbs, coding, prerequisite logic, and implementation support tools.

6 Discussion

The analysis suggests that the most useful educational shift is from compliance-led training to safety-centred competence design. STCW remains indispensable as the minimum regulatory base, but the transition to alternative fuels exposes the limits of relying on minimum standards alone for emerging socio-technical work. IMO's own reliance on interim generic and fuel-specific guidelines confirms that the regulatory system is still catching up with the training implications (IMO, 2025b).

[3] This taxonomy categorizes action verbs into the levels related to the Cognitive, Affective, and Psychomotor domains of learning, helping instructors establish ILOs for specific Levels of Achievement (LoAs) for a specified domain. (IAMU, 2026)

GMP-BoK is useful in this context because it offers a broader educational program through which safety requirements can be translated into learning outcomes, prerequisite structures, delivery choices, and assessment strategies. In other words, it helps bridge the gap between regulatory minimums and future-oriented competence requirements. The significance from a theoretical perspective lies in how it reconceptualises alternative-fuel training as a socio-technical capability issue rather than a simplified fuel-familiarisation issue. From a practical standpoint, it enables MET institutions to address the socio-technical capability issue, particularly considering the evolving detailed regulatory framework.

Conventional Training approaches focus primarily on compliance and/or procedural knowledge; the proposed framework, by contrast, integrates cognitive, affective, psychomotor, and organisational competences. Following the GMP-BoK footsteps, it provides a broader safety-centred structure for safer alternative fuel operation. Although the ongoing STCW comprehensive review discussions and IMO guidance may help reach a satisfactory level of training needs, several identified challenges, not limited to decision-making, alarm management, and team alignment, extend beyond technical skills/capabilities, supporting the needs of more Non-technical skills/capabilities educational approaches.

The paper also contributes to the human-factors discussion by showing that recurrent safety problems in alternative-fuel operations are layered. Cognitive workload, alarm complexity, and interface unfamiliarity are not purely individual limitations; they interact with supervision, organisational updating, scenario realism, and curriculum architecture. This supports the use of multi-domain assessment and scenario-based pedagogy, rather than approaches that rely primarily on written tests or generic emergency drills. In that sense, the paper extends existing discussions of alternative-fuel readiness by specifying what a safety-centred competence system should look like.

MET Institution may begin implementing these guidelines by mapping the curriculum against the mentioned challenge categories and GMP-BoK FAs. Supported by simulator-based training and extended behavioural assessment methods. In addition to establishing a systematic curriculum review system to maintain such alignment. At the same time, the framework has boundary conditions. It does not assume that a single training package will suit all fuels, ship types, automation levels, or institutional contexts. Nor does it claim that GMP-BoK replaces STCW. Rather, the argument is that GMP-BoK can serve as a design scaffold through which institutions organise higher-order competence while remaining consistent with minimum regulatory requirements.

Future research should evaluate the applicability of the proposed guidelines across diverse fuel pathways and educational contexts. A rigorous approach would involve simulator-based experimental studies comparing training programs developed in line with these guidelines with conventional methods. Key performance indicators could include task completion time, adherence to procedures, accuracy in alarm response, situational awareness, decision-making under time constraints, communication effectiveness, error rates during bunkering and emergency operations, and overall safety outcomes. Such empirical investigations would provide robust evidence of the safety-focused training framework's effectiveness and support the refinement of guideline implementation across diverse operational environments.

7 Conclusion

Alternative-fuelling requires a safety-centred training response rather than a technically updated one. A review of the evidence presented in this paper suggests that the transition poses new human factors challenges, including cognitive workload, alarm management, interface unfamiliarity, stress management, emergency response, and organisational readiness. Existing minimum-competence standards are necessary but, alone, are not enough. By combining scenario analysis, HFACS classification, competence mapping, and the GMP-BoK, this paper proposes a set of safety-centred criteria to support training design for alternative-fuel ships. Safer alternative-fuel operations will come from training designs that fuse technical competence with situational awareness, risk management, leadership, communication, resilience, and continuous improvement.

The study has limitations, as it does not empirically test the proposed criteria in a simulator or on-board ships, nor does it suggest that a single model is universally applicable to all fuels, ship types, and organisations. Its contribution is both analytical and prescriptive; it identifies a common safety logic that should apply to all training design and articulates it in a set of contextually flexible guidelines.

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Evaluating Emerging Technologies in Oil Spill Management Through SWOT Analysis: Insights from Multistakeholder Expert Perspectives

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Abstract: Marine oil pollution remains a critical threat to coastal ecosystems, maritime operations, and socio-economic activities, requiring more adaptive and technology-integrated response strategies. Although conventional oil spill response techniques such as mechanical recovery, dispersants, in-situ burning, sorbents, and bioremediation remain operationally important, their effectiveness is often constrained by oil weathering, met-ocean conditions, environmental sensitivity, and response time. This study evaluates conventional and emerging oil spill response technologies through a comparative and SWOT-based framework informed by multistakeholder expert perspectives. Data were obtained from 20 experts representing academics, port authority/environment representatives, maritime practitioners, direct OSR/private response firms, and environmental consultancy experts. The findings show that AI-supported monitoring, autonomous surface and underwater vehicles, advanced sorbents, magnetic nanomaterials, and hybrid response systems can improve early detection, situational awareness, operational safety, and decision-support capacity. However, high investment costs, technical complexity, limited field validation, regulatory uncertainty, training needs, and unequal technological capacity remain major barriers. Overall, the study concludes that emerging technologies should not replace conventional methods, but should complement them within hybrid, phased, and context-sensitive oil spill response systems.

Keywords: comparative analysis, environmental sustainability; expert-based assessment; oil pollution management; oil spill response technologies; SWOT analysis.

1. Introduction

Marine oil pollution has become an increasingly critical environmental and operational concern due to expanding global energy demand, intensified maritime transport, and the continued movement of crude oil and petroleum-derived products across marine environments (Li et al., 2016; Jiao et al., 2019). Oil spill incidents, mostly resulting from anthropogenic activities such as shipping operations, transportation accidents, and offshore energy production, can generate severe ecological, socio-economic, and operational consequences for coastal ecosystems, fisheries, tourism, and maritime activities (Lee et al., 2015; Sardi et al., 2017). Major incidents such as the Deepwater Horizon, Sanchi, and Wakashio spills have demonstrated that oil pollution should not be regarded merely as an isolated operational failure, but as a complex environmental governance challenge requiring rapid detection, coordinated response, and sustainable management strategies (Murphy et al., 2016; Chen et al., 2019; Rajendran et al., 2021).

Effective oil spill response is essential for reducing ecological damage, supporting recovery, and minimizing the economic burden of clean-up and restoration. However, response operations remain challenging because spilled oil is continuously transformed by weathering processes, currents, waves, microbial interactions, and changing oil properties, while operational limitations related to equipment, personnel, logistics, and decision-making further constrain response efficiency (Al-Majed et al., 2012; Ivshina et al., 2015; Li et al., 2016; Yang et al., 2021; Wegeberg et al., 2024). Although conventional response techniques remain important, existing studies have largely focused on the technical performance of individual methods, while strategic and

comparative evaluations of emerging technologies remain limited (Ogbu et al., 2024; Jayarathna et al., 2024; Pessanha Santos et al., 2024). Therefore, this study evaluates emerging oil spill response technologies through a SWOT (Strengths, Weaknesses, Opportunities, and Threats) framework informed by multistakeholder expert perspectives, aiming to provide a more holistic, sustainability-oriented, and operationally grounded basis for adaptive and context-sensitive decision-making in oil spill management.

2. Literature Review

Effective oil spill management requires timely, coordinated intervention supported by contingency planning to reduce risks to human health, coastal areas, and the marine environment (Li et al., 2016; Mohammadiun et al., 2021). Within oil spill response, Strategic planning helps identify high-risk areas before incidents, while tactical response supports post-spill decisions through trajectory and weathering predictions (Grubesic et al., 2017; Singh et al., 2020; Yang et al., 2021). In this context, oil weathering is a key determinant of response selection because it controls the behaviour, persistence, and treatability of spilled oil over time.

2.1. Oil Weathering Processes and Their Implications for Response Selection

Oil weathering processes, including spreading, evaporation, emulsification, dispersion, dissolution, oxidation, sedimentation and biodegradation, dynamically alter oil properties and determine the response window for each technique (Al-Majed et al., 2012; Silva et al., 2022). Early-stage processes mainly influence slick thickness and recoverability, whereas later-stage processes shape persistence, ecological exposure and long-term fate (Li et al., 2016; Jayarathna et al., 2024). Figure 1 illustrates the principal weathering processes that influence the behavior and fate of spilled oil in the marine environment.

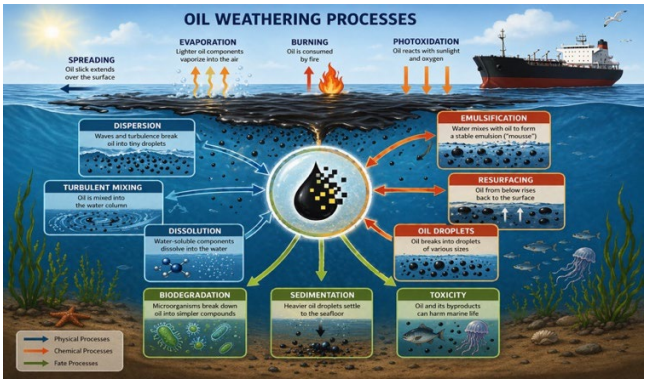


Figure 1. Major weathering pathways of spilled oil in the marine environment adapted from Ivshina et al., 2015.

According to Figure 1., Early-stage weathering processes determine slick thickness and response windows, while later-stage processes influence oil persistence, recoverability, and ecological exposure; therefore, weathering is critical for selecting and adjusting response techniques over time (Li et al., 2016; Keramea et al., 2021; Jayarathna et al., 2024).

2.2. Conventional Oil Spill Response Techniques

Response technologies can be grouped into recovery-based and degradation-based approaches. Mechanical containment and adsorption are generally most relevant during early response, while dispersants, in-situ burning and bioremediation become applicable depending on slick thickness, oil properties, sea state, environmental sensitivity and response objectives (Liu et al., 2022; Silva et al., 2022). Oil spill remediation encompasses a diverse set of techniques that can be broadly categorized into terrestrial and aquatic approaches, as presented in Figure 2.

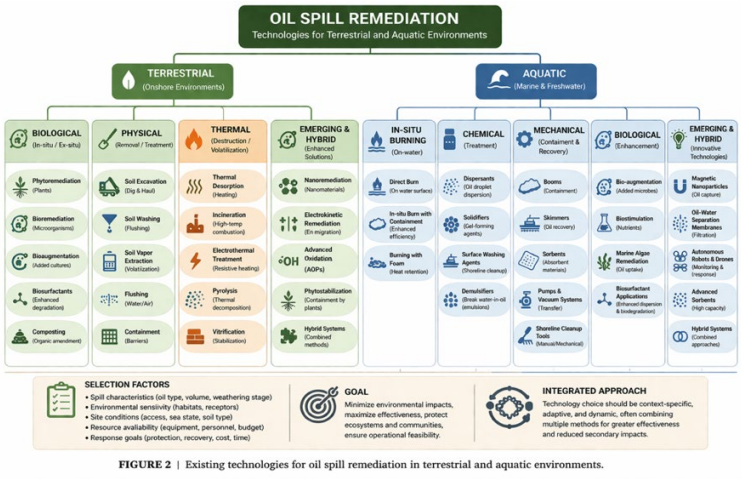


FIGURE 2 | Existing technologies for oil spill remediation in terrestrial and aquatic environments.

Figure 2. Existing oil spill remediation technologies in terrestrial and aquatic environments adapted from Jayarathna et al. (2024).

The effectiveness of these techniques depends on spill type, oil properties, weathering stage, sea state, and operational constraints (Li et al., 2016; Hu et al., 2020; Mohammadiun et al., 2021). These techniques are applied at different spill stages according to oil properties, environmental conditions, response objectives, and operational constraints. This phased approach improves response efficiency and helps reduce environmental impacts (Li et al., 2016; Singh et al., 2020; Silva et al., 2022). This approach highlights the need for adaptive response planning and supports the evaluation of recent high-impact spill incidents presented in Table 1. According to Table 1., Recent ship-source oil spill incidents highlight the need for rapid, coordinated decision-making to reduce shoreline contamination, ecological damage, and socio-economic losses. Therefore, effective response increasingly requires not only conventional measures but also advanced technologies and decision-support tools for complex and time-sensitive spill conditions.

2.3. Emerging and Innovative Oil Spill Response Technologies

Since the Deepwater Horizon spill, oil spill response research has increasingly shifted from conventional methods toward integrated and technology-supported systems, including autonomous vehicles, biomimetic designs, advanced sorbents, nanomaterials, biosurfactant-based dispersants, and AI-supported monitoring tools (Ye, 2022; Yekeen et al., 2020; Jayarathna et al., 2024; Kuzmenko et al., 2026). This shift reflects the limitations of conventional techniques under rough sea states, emulsified oil conditions, sensitive environments, and time-critical scenarios, highlighting the need for more adaptive, scalable, and environmentally sustainable response technologies (Baniasadi and Mousavi, 2019; Singh et al., 2020; Mehmood et al., 2021; Reddy et al., 2022; Hamedi et al., 2023; Prajapat et al., 2025).

AI-supported monitoring tools refer to the integration of satellite imagery, UAV-based observations, remote sensing data, computer vision, and machine-learning algorithms to detect slicks, classify oil-like features, estimate spill extent, and support response prioritization. In operational response systems, these tools can be integrated with trajectory models, GIS-based sensitivity maps, and command-centre decision-support platforms to improve real-time situational awareness and resource allocation.

3. Research Methodology

This study adopts a comparative and SWOT-based methodological framework to evaluate conventional and emerging oil spill response technologies. Prior to ethical approval from the Dokuz Eylul University Human Research Ethics Committee, the draft interview form was reviewed by four independent experts for linguistic clarity, content validity, and practical relevance, and the final version was revised accordingly.

SWOT analysis was selected because the aim of the study was not only to compare the technical performance of individual OSR technologies, but also to evaluate their strategic applicability under real-world operational, environmental, regulatory, and economic constraints. Compared with purely quantitative multi-criteria methods, SWOT provides a more flexible exploratory framework for integrating expert judgement with

literature-based evidence, particularly when emerging technologies are still characterized by limited field validation, uneven operational maturity, and uncertain regulatory acceptance. Therefore, the novelty of using SWOT in this study lies in positioning emerging OSR technologies within a broader strategic decision-making context rather than assessing them solely as isolated technical solutions. Figure 3 illustrates the methodological framework of the study.

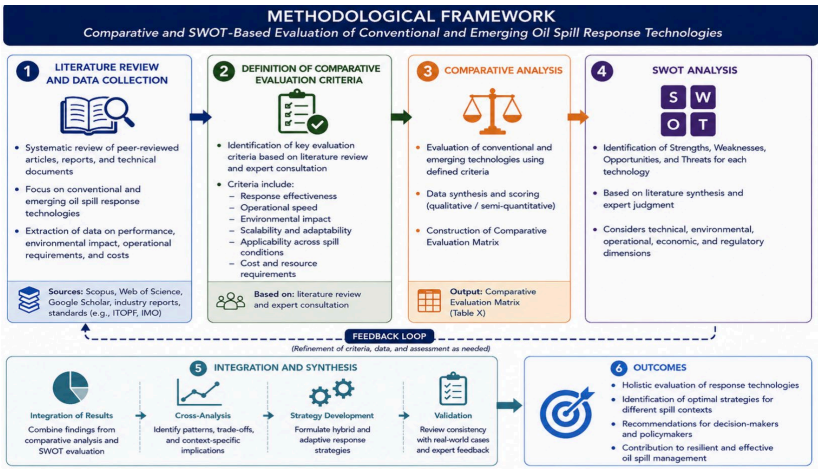


Figure 3. Methodological framework of the study

The methodological framework consists of six sequential stages. First, peer-reviewed studies, reports, and technical documents on conventional and emerging oil spill response technologies were reviewed. Second, evaluation criteria were defined, including response effectiveness, operational speed, environmental impact, scalability, field applicability, regulatory readiness, and cost-related constraints. Third, a comparative analysis was conducted to examine the advantages and limitations of conventional and emerging response options. Fourth, SWOT analysis was used to identify the strengths, weaknesses, opportunities, and threats (Rim-Rukeh, 2015; Alvernia et al., 2021) associated with emerging OSR technologies across technical, environmental, operational, regulatory, and economic dimensions. Fifth, expert judgements were integrated with literature-based findings. Finally, the results were synthesized to provide practical implications for hybrid and context-sensitive oil spill response planning.

The sample size of 20 experts was considered appropriate for an expert-based exploratory SWOT study because the objective was to obtain informed, experience-based judgements from key stakeholder groups rather than to achieve statistical generalization. The experts represented five stakeholder categories, allowing the study to capture academic, operational, regulatory, consultancy, and private-sector response perspectives. Experts were selected using purposive sampling based on their professional relevance to oil spill response, marine pollution management, maritime operations, port/environmental governance, or environmental consultancy. The selection criteria included professional experience in maritime or environmental fields, familiarity with oil spill response technologies or pollution management practices, and the ability to evaluate both conventional and emerging response options from an operational or strategic perspective.

4. Findings

The findings are presented through a two-stage analytical structure that first compares conventional and emerging oil spill response technologies and subsequently examines their strategic implications through expert-based SWOT analysis.

4.1. Comparative Evaluation of Response Techniques

The comparative evaluation examines the operational relevance of conventional and emerging oil spill response techniques under different spill and environmental conditions. As shown in Table 1, recent ship-source oil spill incidents highlight the need for rapid and coordinated decision-making to reduce shoreline contamination, ecological damage, and socio-economic losses.

Table 1. Comparative overview of conventional oil spill response techniques

Technique group	Representative methods	Main strengths	Main limitations	Typical application context
Mechanical recovery	Booms, skimmers, manual recovery	Direct containment and removal; operationally familiar; immediate deployment possible; no chemical addition	Efficiency decreases under rough sea states, strong currents, and emulsified oil conditions; labor- and equipment-intensive; generates oily waste	Nearshore and offshore recovery, calm to moderate sea conditions, first-line response
Sorbents / adsorbents	Natural, inorganic, synthetic sorbents	Simple use; effective for residual oil and small spills; useful in shoreline clean-up	Recovery after use can be difficult; some materials are non-biodegradable; less effective for highly viscous oils; time-consuming over large areas	Small spills, shoreline residues, localized clean-up
Dispersants	Chemical dispersant formulations	Rapid application over large areas: useful when mechanical recovery is impractical; may enhance dilution and biodegradation	Toxicity concerns; uncertain long-term ecological effects; effectiveness depends on oil type, viscosity, and sea energy	Open water, offshore areas, emergency large-scale response
In-situ burning (ISB)	Fire-resistant boom-assisted burning	High short-term removal efficiency; low solid waste generation; useful under limited access conditions	Requires sufficient slick thickness; weather-dependent; causes air emissions and secondary pollution concerns	Offshore or remote spills, thick slicks, resource-constrained emergencies
Solidifiers	Oil-gelling / polymer-based solidifiers	Immobilizes floating oil; can simplify physical recovery in localized spills	Requires large material quantities; not widely used operationally; recovery of solidified mass may be difficult	Small spills, edge containment, localized response
Bioremediation	Nutrient addition, microbial enhancement	Environmentally compatible; supports long-term hydrocarbon degradation; suitable for ecological restoration	Slow action; strongly dependent on temperature, oxygen, nutrients, and site conditions; limited value for acute emergency removal	Shorelines, wetlands, residual contamination, post-response polishing
Natural attenuation	Monitored natural recovery	Minimal intervention cost; avoids additional operational disturbance in some cases	Slow and uncertain; requires strong monitoring; not acceptable where sensitive resources are at immediate risk	Low-risk or low-access sites, residual contamination, monitored recovery phase

As shown in Table 1, conventional techniques differ in their strengths and limitations, confirming that no single method is universally effective across all spill scenarios. Mechanical recovery enables direct containment and removal but is sensitive to rough seas and emulsified oil, while dispersants offer rapid large-area application but raise ecological concerns. In-situ burning may provide high short-term removal efficiency, whereas bioremediation is more environmentally compatible but slower and condition-dependent (Ivshina et al., 2015; Liu et al., 2022; Techtmann et al., 2023; Jayarathna et al., 2024; Brandvik et al., 2025). Table 2 summarizes emerging technologies that aim to overcome some limitations of conventional methods.

Table 2. Comparative overview of emerging and innovative oil spill response technologies

Technology category	Representative innovation	Main advantage	Main limitation	Typical application potential
Advanced mechanical recovery	Smart booms, fire-resistant booms, improved oleophilic/vacuum skimmers	Improves containment and recovery efficiency; suitable for rapid first-line intervention; more targeted than conventional systems	Still highly sensitive to rough seas, strong currents, access constraints, and equipment complexity	Nearshore and offshore response, thick slick recovery, operationally controlled conditions
High-performance sorbent materials	Advanced synthetic sorbents, reusable porous materials, aerogel-like absorbents	High oil uptake, lightweight structure, potential reusability, effective for residual slicks and shoreline clean-up	Recovery, disposal, and large-scale deployment remain challenging; some materials are costly or not easily biodegradable	Small-to-medium spills, shoreline residues, polishing operations
Magnetic nanomaterial-based adsorbents	SPIONs, magnetic nanocomposites, magnetic carbon-based sorbents	High adsorption capacity, magnetic recovery, reusability, hydrophobic/oleophilic behaviour	Large-scale field application, commercialization, toxicity testing, and recovery logistics remain unresolved	Oil–water separation, emulsified oil treatment, pilot-scale clean-up systems
Improved chemical dispersion systems	Nano-enabled dispersants, lower-dose dispersive formulations, selective surfactant systems	Faster oil breakup, improved spreading control, potential reduction in dosage, useful where mechanical recovery is limited	Ecotoxicological uncertainty, regulatory concerns, oil-type dependency, and secondary pollution risk remain significant	Open-water emergency response, offshore large-area spills
Environmentally friendly solidification systems	Low-toxicity solidifiers, bio-based gelling materials	Can immobilize floating oil and facilitate later recovery; reduces spill mobility	High material demand, limited field-scale application, and difficulty in recovering gelled oil	Localized floating spills, edge containment, targeted intervention zones
Enhanced bioremediation approaches	Nutrient-assisted biodegradation, bioaugmentation, enzyme- or microbial-support systems	Environmentally compatible; supports long-term degradation; lower secondary pollution risk	Slow response time; highly dependent on temperature, oxygen, nutrients, and site conditions	Shorelines, wetlands, residual contamination, post-emergency recovery
Autonomous surface and underwater vehicles	ASVs, AUVs, autonomous monitoring craft	Enable rapid surveillance, continuous monitoring, and access to hazardous or remote spill zones with reduced human exposure	High investment cost, maintenance requirements, limited endurance, and navigation constraints in harsh conditions	Offshore monitoring, spill tracking, inaccessible or high-risk environments

ROV-based intervention systems	Remotely operated vehicles for inspection, leak localization, subsea monitoring, targeted intervention	Highly useful in hazardous subsea environments; improves inspection accuracy and supports source control	Operator dependence, limited range, operational complexity, and high equipment cost	Subsea leaks, wreck inspection, underwater source detection, pipeline and tanker accident zones

Advanced sorbents, magnetic nanomaterials, biosurfactant-based dispersants, autonomous systems, ROVs, and AI-supported monitoring tools offer advantages in recovery efficiency, early detection, operational safety, and decision support. However, their broader adoption is constrained by cost, scalability, field validation, technical complexity, and regulatory uncertainty (Mehmood et al., 2021; Farooq et al., 2024; Prajapat et al., 2025; Du et al., 2025). Therefore, the diversity of response options requires a structured evaluation framework to compare their strategic strengths, limitations, opportunities, and threats.

4.2. SWOT Analysis Findings

The SWOT analysis was conducted based on the evaluations of 20 experts representing five stakeholder groups: academics, port authority/environment representatives, maritime practitioners, OSR/private response firms, and environmental consultancy experts. Figure 4 summarizes the expert-based SWOT evaluation of OSR technologies.

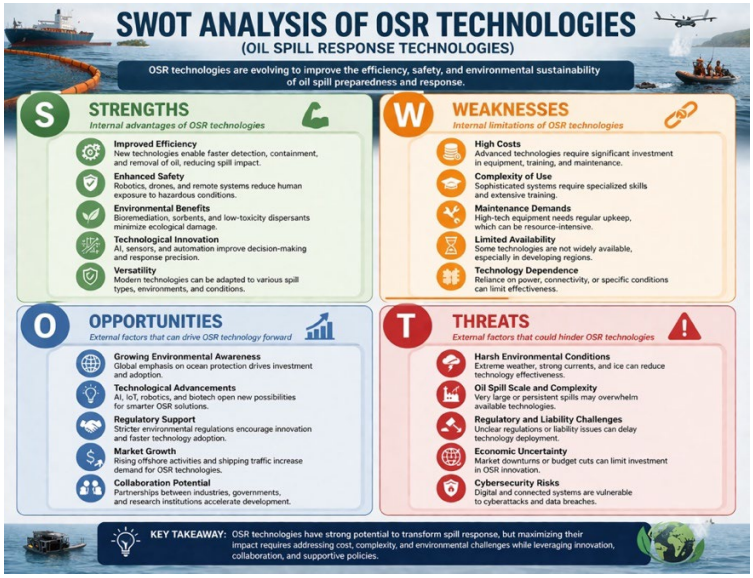


Figure 4. SWOT Analysis Based on Expert Judgement

According to SWOT Analysis based on expert judgements, it shows that emerging technologies offer clear strengths in efficiency, safety, environmental performance, and decision-making, while their wider use is limited by cost, technical complexity, maintenance needs, and regulatory uncertainty. Overall, the figure supports the need for hybrid response strategies combining conventional methods with innovative technologies.

The SWOT results indicate that the main strengths of emerging OSR technologies are associated with faster detection, improved situational awareness, reduced human exposure in hazardous spill environments, and enhanced decision-support capacity. AI-supported monitoring tools, autonomous vehicles, and advanced sorbent or nanomaterial-based systems can contribute to more adaptive and targeted response operations. However, the weaknesses are mainly related to high investment costs, technical complexity, maintenance requirements, limited field validation, and the need for specialized training. The opportunity dimension shows that emerging technologies may support digitalized contingency planning, real-time monitoring, environmentally sensitive response, and hybrid response strategies. By contrast, the threat dimension reflects regulatory uncertainty, unequal access to advanced technologies, possible ecological risks from chemical or nano-enabled materials, and institutional preparedness gaps. Therefore, the SWOT findings suggest that the future role of emerging OSR technologies depends on their integration with conventional response systems rather than their independent use.

The open-ended expert comments reinforce the quantitative SWOT results by showing that the future effectiveness of OSR technologies depends on integration rather than replacement**.** Experts identified AI-supported monitoring, autonomous surface/underwater vehicles, advanced sorbents, and hybrid response systems as the most promising options due to their potential to improve early detection, reduce human exposure, and support faster decision-making. However, they also emphasized persistent barriers, including high costs, limited field validation, lack of trained personnel, regulatory uncertainty, and insufficient institutional readiness. Overall, the findings support a hybrid, phased, and context-sensitive response model in which conventional techniques provide operational reliability, while emerging technologies enhance monitoring, decision support, environmental performance, and long-term preparedness.

5. Discussion and Conclusion

The findings indicate that emerging oil spill response technologies are increasingly regarded as important components of modern oil pollution management, but not as direct substitutes for conventional techniques. This is consistent with previous studies showing that mechanical recovery, dispersants, in-situ burning, sorbents, and bioremediation remain operationally relevant, although their effectiveness depends on oil type, weathering stage, sea state, response time, and environmental sensitivity (Ivshina et al., 2015; Li et al., 2016; Moroni et al., 2019; Jayarathna et al., 2024). The expert-based SWOT results further show that AI-supported monitoring, autonomous vehicles, advanced sorbents, magnetic nanomaterials, and hybrid response systems offer strong potential for improving detection, situational awareness, operational safety, and decision-making, supporting earlier findings on digitalization and decision-support tools in complex marine spill response (Hu et al., 2020; Mohammadiun et al., 2021; Yang et al., 2021; Ye et al., 2024). However, the relatively judgements for Weaknesses and Threats reveal that emerging OSR technologies still face important implementation barriers, including high investment costs, technical complexity, limited field validation, training needs, regulatory uncertainty, and institutional readiness. These concerns are in line with recent studies emphasizing scalability, operational reliability, environmental risk assessment, and integration challenges in innovative response systems (Jayarathna et al., 2024; Prajapat et al., 2025; Kuzmenko et al., 2026).

Environmental risks should also be considered when evaluating emerging OSR technologies. Although magnetic nanomaterials and nano-enabled sorbents may improve oil adsorption and recovery efficiency, their possible ecotoxicological effects, persistence, recovery efficiency after deployment, and interaction with marine organisms remain important concerns (Mehmood et al., 2021; Hemadi et al., 2023). Similarly, chemical and biosurfactant-based dispersants can enhance oil dispersion and biodegradation under suitable conditions, but they may also increase the short-term exposure of water-column organisms to dispersed oil components. Therefore, the operational use of these technologies should be supported by site-specific environmental risk assessment, toxicity testing, regulatory approval, and post-response monitoring.

The adoption of emerging OSR technologies may also vary significantly across regions due to differences in financial resources, technical infrastructure, trained personnel, regulatory capacity, and access to specialized response equipment. This is particularly important for developing or resource-constrained maritime regions, where conventional response systems may remain dominant despite the growing availability of digital and autonomous technologies.

Long-term maintenance and lifecycle costs are another critical issue. Autonomous vehicles, AI-supported monitoring systems, advanced sensors, and nano-enabled response materials may require continuous calibration, software updates, technical maintenance, operator training, and replacement of specialized components. Therefore, cost assessment should consider not only initial investment, but also lifecycle operation, maintenance, training, storage, and disposal costs.

This study evaluated conventional and emerging oil spill response technologies through a comparative and expert-based SWOT framework. The findings show that emerging technologies offer strong potential to improve detection, situational awareness, operational safety, environmental performance, and decision-support capacity. However, high cost, technical complexity, limited field validation, training needs, regulatory uncertainty, and unequal technological capacity remain key barriers. From an implementation perspective, the findings show that emerging OSR technologies should be evaluated not only in terms of technical performance, but also in relation to environmental risk, institutional readiness, operational integration, and lifecycle cost. AI-supported monitoring systems can strengthen early detection and decision support when integrated with satellite

imagery, UAV observations, GIS-based sensitivity maps, and trajectory modelling platforms. However, their effectiveness depends on data quality, trained operators, communication infrastructure, and command-centre integration. Similarly, autonomous vehicles and ROV-based systems can reduce human exposure and improve monitoring in hazardous or inaccessible areas, but their use requires maintenance capacity, endurance planning, operational protocols, and investment in technical training. In addition, the use of magnetic nanomaterials, nano-enabled sorbents, and dispersant systems should be carefully assessed due to possible ecological risks, regulatory uncertainty, and post-deployment recovery challenges. These issues suggest that technological innovation in oil spill response must be accompanied by institutional preparedness, environmental safeguards, and long-term cost planning.

The main scientific contribution of this study is its integrated evaluation of OSR technologies beyond single-method assessments, combining comparative analysis with multistakeholder expert judgement. The results indicate that innovative technologies should not replace conventional methods, but should be embedded in hybrid, phased, and context-sensitive response systems.

Since this study was designed as an exploratory SWOT-based assessment, it did not apply quantitative weighting or ranking methods such as AHP, TOPSIS, or other multi-criteria decision-making techniques. Future research should validate these findings through real spill scenarios, simulation-based testing, expert-based weighting of SWOT dimensions, and multi-criteria decision-making models such as AHP, TOPSIS, or fuzzy MCDM approaches. Such extensions would allow the ranking of emerging OSR technologies according to operational effectiveness, environmental risk, cost, scalability, and institutional readiness.

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Cyber-Physical Risks in Remote-Controlled Nuclear-Powered Merchant Vessels

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Abstract: Remote operations are emerging as a pivotal enabler for future nuclear-powered merchant vessels, allowing for shore-based machinery propulsion supervision and a reduction in onboard nuclear operator specialists. However, this digital dependency shifts the risk profile towards systems cybersecurity. This paper explores the cyber-physical risks associated with satellite-dependent monitoring and remote access pathways in nuclear-powered commercial vessels. By viewing the vessel as integrated part of an interconnected ecosystem involving Remote Operations Centres and satellite data providers, critical vulnerabilities in information and operational technology are identified. This study proposes practical safeguards measures, including Information Technology / Operational Technology (IT/OT) segregation based on the International Electrotechnical Commission 62443 series of international standards, the use of unidirectional data diodes, and degraded mode procedures, alongside a multi-profile training approach for personnel onboard vessels aligned with requisites of International Convention on Standards of Training, Certification and Watchkeeping for Seafarers of International Maritime Organization.

Keywords: maritime cybersecurity; nuclear propulsion; remote operations; maritime education and training

1. Introduction

The maritime industry is undergoing a dual paradigm shift driven by the decarbonisation of shipping—through the prospective adoption of nuclear propulsion, notably by using new Generation IV reactors such as Small Modular Reactors (SMRs)—and by the increasing digitalisation of ship operations via Remote Operations Centres (ROC). While nuclear propulsion offers near-zero carbon emissions and exceptional energy density, its integration into remotely operated merchant vessels fundamentally alters the vessel's risk profile by introducing new cyber-physical dependencies.

In this context, the deployment of SMRs in merchant shipping is not fundamentally a question of technological feasibility, but of security of the vessel. As highlighted in the NuProShip I final project report (Emblemsvåg et al., 2025), the reduction of specialised personnel onboard vessels increases reliance on robust, low-latency communication links to maintain operational reactor safety (CCDCOE, 2022). As safety-critical functions become increasingly mediated through digital connectivity, reactor safety and vessel integrity may be compromised not only by technical failures, but also by cyber incidents targeting information and operational technologies (IMO, 2025).

This paper examines the emerging cyber-physical risks by analysing the vessel as part of a wider and complex digital ecosystem that includes shore-based operations and external communication infrastructures. While insights from other safety-critical industries are relevant, in this paper a special attention will be given to the broader cross-sectoral and organisational implications of remote operations in nuclear-powered vessels.

This paper develops a conceptual framework that links the vessel ecosystem described in Section 2 to three interdependent controls: an IEC 62443-based zone-and-conduit architecture, Digital Twin-supported anomaly detection, and multi-profile maritime training. The proposal is deliberately conceptual: the proposed architecture and competency model are derived from literature on maritime cybersecurity, nuclear safety

engineering and offshore integrated operations, and should be treated as a basis for expert validation, simulation-based testing and later field trials.

2. The Vessel as a System

A nuclear-powered merchant vessel cannot be analysed as an isolated unit. Rather, it constitutes a highly integrated ecosystem comprising electrical, mechanical, physical, chemical, and digital subsystems. The safe and reliable operation of such a vessel depends on the interaction of multiple distributed components that collectively support the Nuclear Propulsion System (NPS).

In this context, three system elements are particularly critical:

- Remote Operations Centre (ROC): A shore-based facility responsible for monitoring nuclear reactor telemetry and providing expert decision support by onboard personnel.
- Satellite Communication (SatCom) Segment: The primary communication interface between ship and shore-based ROC. Research on the SatCom user segment demonstrates that satellite links cannot be treated as trusted by default and therefore require efficient layered security and protection mechanisms (Casaril and Galletta, 2024).
- Reactor Vendor Infrastructure: External digital pathways that support remote maintenance functions, including software updates and real-time diagnostics of the Nuclear Propulsion System (NPS).

Together, these components form a tightly coupled cyber-physical system in which operational continuity and safety depend on the availability, integrity, and reliability of interconnecting digital interfaces. While this section focuses on the technical composition of the vessel ecosystem, the broader implications of these dependencies—particularly their role in shaping operational risk under remote and distributed control are discussed later in the paper.

Unlike traditional information technology (IT) systems, attacks targeting Operational Technology (OT) have direct physical consequences. In nuclear-powered vessels, where control integrity and real-time feedback is essential for safe operation, cyber incidents affecting OT can rapidly escalate into ship safety-critical situations.

The following attack vectors are therefore of particular concern (NIST, 2023):

- Sensor Spoofing: Manipulating reactor coolant temperature or pressure data to provoke an automated emergency shutdown – Safety Control Rod Axe Man (SCRAM) - or, worse, to mask a real overheating event.
- Control Loop Interference: Unauthorised access to the Maritime Control Systems (MCS) can interfere with the primary or secondary cooling loops, potentially leading to core damage.
- Latency-Induced Instability: Disruption in satellite links leads to a loss of situational awareness. For a nuclear reactor, the occurrence short periods of uncertainty or degraded monitoring increase risk and make emergency response more demanding (EMSA, 2024).

These vulnerabilities illustrate how cyber intrusions at the operational level can be translated directly into physical hazards; however, they represent only part of the broader risk landscape associated with remote nuclear operations, which is further examined in the following sections.

3. Cyber-Physical Architecture: Zones and Conduits (IEC 62443)

To protect a nuclear-powered merchant vessel from remote cyber threats, it is necessary to adopt a defence-in-depth cybersecurity architecture based on the IEC 62443 zone-and-conduit model (IEC, 2018). In the proposed design, security zones separate assets according to criticality and trust level, while conduits define the controlled communication paths between them. Figure 1 operationalises this principle for the vessel ecosystem introduced in Section 2 by distinguishing the Nuclear Safety Zone, the Marine Control Zone, the Satellite Gateway Conduit, the shore-based ROC and the reactor vendor infrastructure. The failure/attack distinction behind these design choices is then synthesised in Table 1 before the discussion turns to Digital Twin-based anomaly detection.

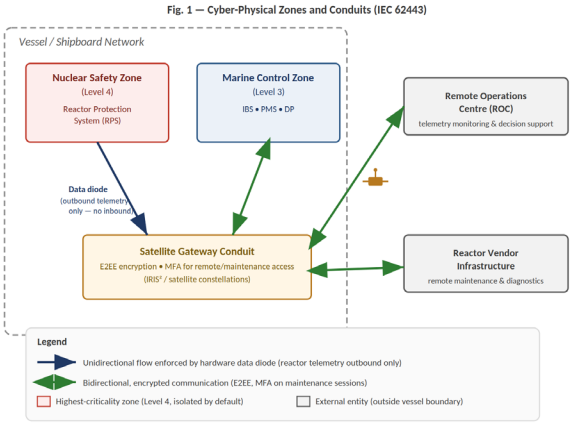


Figure 1. Proposed IEC 62443-based cyber-physical zones and conduits for a remote-controlled nuclear-powered merchant vessel.

Table 1. Distinction between traditional failures and cyber-physical attacks in critical ship systems.

System Component	Traditional Technical Failure	Cyber-Physical Attack (Malicious)
Coolant Sensors	Sensor drift (Fail-safe trip)	Data Hijacking: Sensors report normal levels while overheating
Satellite Communication Link	Signal loss due to adverse environmental conditions (e.g. severe weather)	Signal Spoofing: Vessel follows fake GPS path; ROC is presented with misleading normal-looking navigation data
Satellite Gateway Conduit	Link degradation due to bandwidth congestion	Man-in-the-middle interception of E2EE session, enabling command injection during maintenance access
Remote Access Interface	Maintenance software bug	Backdoor Entry: Ransomware encrypts the Nuclear Propulsion System (NPS) control interface
Emergency Shutdown	Mechanical failure of rods	Logic Manipulation: Disabling SCRAM logic via Programmable Logic Controllers (PLC) firmware attack

3.1. The Nuclear Safety Zone (Level 4)

This zone encompasses the Reactor Protection System (RPS) and associated safety-critical components. By design, the Nuclear Safety Zone is isolated by default from all other networks and systems. In practice, this isolation is achieved through unidirectional data diodes at the zone boundary. These hardware-enforced one-way communication devices ensure that reactor telemetry can flow outward to the ROC for monitoring, but no external commands or data packets are able to flow inward to the RPS. This security architecture at the physical layer prevents any malicious input from reaching the reactor's core control logic, thereby protecting the integrity of critical safety functions.

3.2. The Marine Control Zone (Level 3)

The Maritime Control Zone comprises the vessel's non-nuclear operational systems, including the Integrated Bridge System (IBS), the vessel Power Management System (PMS), and (when applicable) the Dynamic Positioning (DP) system. This zone interfaces directly with external communications and is therefore a primary target for protocol spoofing attacks. For example, if an intruder were to compromise the satellite communications link, they could inject spoofed National Marine Electronics Association (NMEA) navigation messages. Such an attack might alter the vessel's course or other operational parameters while simultaneously feeding falsified "normal" status information back to the shore-based ROC, thereby deceiving operators about the true situation of the ship.

3.3. The Satellite Gateway Conduit

The Satellite Gateway Conduit is the communications channel linking the vessel to remote networks via satellite constellations (e.g., IRIS²). This conduit is one of the most exposed points of the architecture, as it handles all bidirectional data exchange between on-board systems and external entities. To secure this link, robust cryptographic measures such as end-to-end encryption (E2EE) must be employed, alongside stringent

authentication controls like multi-factor authentication (MFA) for any remote access or maintenance sessions. These measures help ensure that data in transit cannot be easily intercepted or manipulated by malicious agents. Note that even a rigorous security-by-design architecture such as the one outlined in this section can only mitigate—not entirely eliminate—the broader socio-technical risks inherent in remote nuclear operations. Issues such as human factors, organisational processes, and unanticipated system interactions require additional measures, which will be discussed in the next sections.

To connect the architectural model with operational risk analysis, Table 1 contrasts conventional technical failures with malicious cyber-physical attacks for selected components of the vessel ecosystem. This distinction is essential because identical operational symptoms—such as abnormal telemetry, degraded communications or loss of remote access—may require different responses depending on whether they arise from equipment failure or from intentional manipulation.

In summary, Table 1 acts as the analytical bridge between the zone-and-conduit architecture represented in Fig. 1 and the Digital Twin mechanism that will be discussed in Section 4. If sensor values, navigation data or remote-access sessions are compromised, a threshold-based alarm may be insufficient; the ROC needs an independent means of checking whether the received data remain physically plausible.

4. Digital Twins for Anomaly Detection and Remote Operations

A sophisticated mitigation method involves the use of a Digital Twin at the ROC. By running a real-time physics-based simulation of the vessel's reactor, operators can cross-verify received telemetry data. If the ship's data deviates from the Digital Twin's predictions (e.g., pressure rises without a corresponding temperature increase), the system flags a Cyber-Physical Inconsistency, allowing the detection of stealthy attacks that standard threshold alarms would miss.

4.1. Comparative Analysis of Remote Operations: From Oil and Gas to Nuclear Propulsion

Over the past two decades, remote operations—often termed integrated operations in the oil and gas sector—have fundamentally transformed how offshore oil and gas facilities are managed. Advances in high-speed satellite communications have enabled expert teams at onshore control centres to remotely support and monitor offshore drilling and production activities in real time, leading to more centralised decision-making and reduced crew presence at remote sites (Gillan et al., 2018; Hepsø & Parmiggiani, 2022). The oil and gas industry's experience is instructive for maritime nuclear propulsion, as both contexts involve complex, high-risk socio-technical systems that depend on highly skilled personnel, rigorous safety management, and robust shore-based supporting organisations.

Studies of integrated operations in oil and gas (O&G) industry generally report benefits to operational efficiency and routine safety performance. For instance, the adoption of remote operation practices has been associated with measurable improvements in productivity and reduced downtime (Chmela et al., 2020; Hildebrand et al., 2017). In parallel, certain safety indicators—primarily the frequency of occupational incidents and other minor events—have shown improvement following the introduction of remote operations (Albrechtsen & Weltzien, 2013; Johnsen et al., 2024). These gains are typically reflected in industry health, safety, and environment (HSE) statistics. A persistent concern, however, is the occurrence of major accidents (or system accidents) in high-hazard industries. Extensive safety research indicates that trends in minor incidents have little correlation with the likelihood of rare but catastrophic system-level accidents, since the causative factors often differ fundamentally (Albrechtsen & Weltzien, 2013; Deming, 2018). In other words, remote operations can achieve notable reductions in day-to-day incident rates without necessarily reducing the risk of a major accident—a phenomenon metaphorically described as a "Janus-faced" aspect of integrated operations (Albrechtsen & Weltzien, 2013).

These findings from the O&G domain raise critical questions about how remote operations might influence the safety of nuclear-powered vessels. In particular, if remote operations in oil and gas are simultaneously linked to safety improvements in routine activities and to unresolved vulnerabilities associated with major accidents, how might a similar paradigm play out in the nuclear maritime context, where the stakes are even higher? This open question underpins the cross-sectoral analysis and organisational risk implications to be addressed in the analysis that follows.

4.2. Lessons from Integrated Operations: Cross-sectoral Insights for Nuclear Propulsion

The transition towards remote operations in nuclear-powered merchant vessels does not occur in a technological vacuum. While this paradigm is novel to the shipping, the oil and gas industry's decades-long experience with integrated operations provides valuable lessons for understanding the opportunities and pitfalls of relocating critical functions from offshore sites to shore-based remoted control centres. In O&G, reconfiguring operations in this way has delivered substantial improvements in operational efficiency and reductions in routine safety incidents (Chmela et al., 2020; Johnsen, Thyme & Myklebust, 2024). However, these gains have come at the cost of added socio-technical complexity, which serves as a cautionary example when considering the deployment of Small Modular Reactors (SMRs) under remote supervision.

A core insight from O&G is the dual, "Janus-faced" nature of remote integrated operations in relation to major accident prevention (Albrechtsen & Weltzien, 2013). On one hand, transferring decision-making and oversight onshore facilitates safety by leveraging real-time telemetry and expert analysis to address anomalies or minor incidents before they escalate, thus strengthening day-to-day operational reliability. On the other hand, the reliance on digital connectivity and remote coordination introduces layers of organisational and technological complexity that can inadvertently heighten the risk of catastrophic "system accidents". These are not triggered by a single component's failure but rather emerge from unanticipated interactions across numerous interdependent systems (Deming, 2018). In other words, as critical processes become more distributed across vessels, satellites, and ROCs, the system's overall risk profile shifts: routine incidents may decrease, but the potential for rare, high-consequence accidents may persist or even increase due to the expanded attack surface and intricate interconnectivities.

This paradox is especially pertinent for nuclear propulsion, where risk tolerance is effectively zero. In contrast to O&G – where regulators and industry have traditionally managed a non-zero background level of risk and infrequent major accidents – maritime nuclear operations demand near-perfect prevention due to the extreme consequences of a reactor-related mishap. The negligible tolerance for error in the nuclear realm means that remote operational models must be designed with even more stringent safeguards and a holistic understanding of risk. Therefore, methodologies for risk analysis must evolve beyond conventional techniques. Traditional engineering risk assessments, effective for evaluating mechanical reliability and individual component failures, are insufficient to capture the human and organisational factors introduced by a highly digital, distributed control environment (Andersen & Mostue, 2012). To bridge this gap, this paper emphasises the need for a resilience-based risk assessment approach tailored to remote nuclear operations. Such an approach prioritises the system's capacity to anticipate, absorb, and adapt to complex failures, focusing on how well the organisation can respond to emergencies that span both cyber and physical domains.

Practical implication of this resilience perspective is the elevated role of Digital Twins in remote nuclear propulsion. Earlier in this paper, Digital Twins were introduced as a high-fidelity tool for anomaly detection, comparing sensor data with a real-time physics-based model of the reactor. Here, we emphasize that the Digital Twin's utility must extend further: as a platform for shared situational awareness and collaborative decision-making. When both the onboard crew (even if reduced) and the ROC staff operate based on a common, validated Digital Twin of the reactor, they develop overlapping competencies and a mutual understanding of the reactor's state and dynamics. This joint cognitive framework fosters resilience by enabling the team to detect discrepancies early—whether due to technical faults, communication lags, or malicious data manipulation—and to coordinate an effective response even under degraded conditions. In essence, the Digital Twin should act not merely as a monitoring instrument, but as a socio-technical bridge that maintains system integrity and operator confidence when direct communication channels are strained or compromised.

By learning from O&G integrated operations and adapting through a lens of risk intolerance, the maritime nuclear sector can proactively address the "Janus-faced" trade-offs of remote control. This means reinforcing the positive aspects (e.g., enriched data-driven safety measures) while mitigating the negatives (e.g., communication vulnerabilities and complexity-induced hazards) via design and planning. Achieving these outcomes not only requires technical solutions, like the technical measures discussed earlier, but also a fundamental shift in how personnel are prepared for their roles. It becomes imperative that maritime professionals develop hybrid skill sets encompassing both mechanical and electrical systems, and digital infrastructure, to effectively manage the unique challenges of a cyber-physical nuclear reactor environment. This human-capital dimension is therefore crucial, requiring an adequate evolution of maritime education and

training programs in order to build the required multi-domain competencies for safe and resilient remote nuclear operations.

5. Maritime Education and Training in Nuclear-powered Vessels: A Multi-Profile Approach

As emphasised earlier, implementing a robust technical architecture and resilience measures is only one part of the solution. Operationalising the resilience requirements identified earlier necessitates a comprehensive approach to human and organisational capacity building. To achieve this goal, the maritime sector must adopt multi-profile education and training programmes that train personnel at all levels with the skills required to manage cyber-physical challenges in remote nuclear operations.

A three-tier competency model aligned with STCW Convention requisites is proposed in the following to structure these efforts:

1) Onboard Skeleton Crew: Focused on recognising cyber-induced mechanical and electrical failures and activating degraded mode protocols (manual overrides) when data cannot be trusted
2) Shore-Based ROC Operators: Trained in secure communication protocols and remote crisis management under time pressure and intermittent connectivity
3) Emergency Response Teams (ERT): Specialized in recovering systems after ransomware or intrusions that affect nuclear reactor stability and control systems.

Beyond these role-specific tiers, the training model must address the cognitive and organizational demands defined in the architecture of Fig. 1 and the anomaly-detection logic discussed in Section 4, ROC operators may be required to monitor multiple vessels concurrently, increasing workload and the risk of attention tunneling during anomaly detection. Automation complacency is a further concern: sustained reliance on Digital Twin cross-verification may erode manual diagnostic skills that become critical precisely when digital trust is compromised. Training programs should therefore explicitly address situational awareness under degraded connectivity, shared mental models between onboard and shore-based teams, and decision-making under the time pressure characteristic of safety-critical, low-tolerance environments.

To support these tiers, training structures need to simulate realistic cyber-physical crisis scenarios. One essential method is the integration of “Cyber-Sprints”—high-intensity cyber-physical simulation exercises—into engine room and bridge training simulators. These training exercises are designed to test and enhance the ability of seafarers and ROC operators to distinguish between mechanical and electrical malfunctions and deliberate data manipulation or network disruption. By immersing trainees in scenarios where the digital situational picture is degraded or is deceptive, such as false sensor readings or delayed commands, Cyber-Sprints foster the skills needed to maintain control and ensure reactor and vessel safety when normal operating conditions are compromised.

In tandem with new training practices, there are significant certification implications. To formalise these multi-domain competencies, this paper recommends revising relevant STCW competency tables (specifically those in Chapters II, III, VI and VIII), which define standards for deck officers, marine engineer officers, electrotechnical officers, and watchkeeping procedures (Morland, 2023; Morland, Schøyen and Emblemsvåg, 2026). The goal is to incorporate explicit requirements for cyber-physical system management, crisis response, and cross-disciplinary technical skills. A key proposal is the establishment of a “Nuclear-Cyber Endorsement”—a specialised qualification under the STCW framework which certifies that a maritime professional has demonstrated proficiency in managing the unique safety challenges posed by digitally integrated SMR-based propulsion systems. This endorsement would ensure that personnel operating or overseeing ROCs and nuclear-powered vessels have the necessary training to address the physical implications of digital intrusions.

By implementing this multi-profile training and certification approach, maritime stakeholders can operationalise resilience: bridging the gap between advanced technological systems and the human expertise required to use those systems effectively. In doing so, the industry will foster a workforce capable of navigating the complex, hybrid demands of remote nuclear ship operations, thereby aligning operator competencies with the technical measures discussed earlier.

6. Economic and Regulatory Considerations

A key incentive of remote nuclear operations is reduced crew size, due to the increase of automation and control systems onboard which reduce the vessel's operating expenditures (OPEX) by cutting onboard specialist costs. However, it is crucial to strategically reinvest these OPEX savings to address the enhanced risk complexity introduced by remote and digital operation as presented earlier. In particular, is crucial to reinvest in the following three priority areas:

- Redundancy in Critical Connectivity: The adoption of remote control in nuclear propulsion makes uninterrupted communication an existential necessity. To guard against communication loss or manipulation, multiple independent satellite links (both LEO and GEO) should be maintained for the ship-to-shore data connection. Such redundancy mitigates the risk of a single point of failure in connectivity and addresses the socio-technical vulnerabilities identified earlier in this paper;
- Cybersecurity Management System Integration: The industry must integrate cyber risk management into the shipboard Safety Management System (SMS), as mandated by emerging IMO guidelines (e.g., MSC-FAL.1/Circ.3, aligned with IMO Resolution MSC.428(98)). This means establishing a dedicated Cyber-Security Management System (CSMS) as part of every vessel's SMS, thereby ensuring that digital threats are continuously monitored, controlled, and accounted for alongside traditional safety risks. Reinvesting in a robust CSMS and regular audits will help manage the complex cyber-physical risk environment inherent to SMR operations;
- Certification and Regulatory Harmonisation: The successful deployment of nuclear propulsion requires close regulatory coordination between the IMO and the International Agency of Atomic Energy (IAEA). Specifically, harmonised certification processes must be developed for the type-approval of SMR installations with integrated cyber-defences. This alignment will ensure that any SMR technology intended for marine use meets maritime safety standards while also satisfying nuclear security requirements, filling a current gap in regulatory frameworks and providing confidence to stakeholders and flag states.

By channelling the cost savings from reduced onboard crew into connectivity, cybersecurity governance, and regulatory alignment, the maritime industry can strengthen the feasibility and safety of remote nuclear operations. These economic and regulatory investments, made in anticipation of the increased risk complexity of remote nuclear propulsion with SMR, are crucial for bridging the governance gaps and ensuring that the decarbonisation potential of nuclear propulsion is realised without compromising safety and security of shipping.

7. Conclusion

The transition in shipping towards nuclear-powered, remotely operated merchant vessels ultimately hinges on reconciling nuclear safety with cybersecurity in remote operations, requiring a coordinated governance framework that integrates technical architecture, organisational resilience, and human capital development. As highlighted earlier, a Security-by-Design approach grounded in IEC 62443 architectures, strict IT/OT segregation, and physical safeguards such as data diodes provides a necessary engineering foundation for mitigating cyber-physical threats. However, technical measures alone are insufficient to address the complexity of risk introduced by remote and digitally mediated nuclear operations, where system-level interactions and low tolerance for failure demand a resilience-oriented perspective.

Within this context, regulatory alignment becomes a critical enabler. Close cooperation between the International Maritime Organization (IMO)—notably under MSC.428(98)—and the International Atomic Energy Agency (IAEA) is essential to ensure that cybersecurity is fully integrated into nuclear safety oversight. In particular, the mandatory incorporation of a Cyber-Security Management System (CSMS) within the vessel's Safety Management System (SMS) provides a governance mechanism that connects architectural safeguards with operational risk control.

Equally central to this framework is the role of human capital, addressed through multi-profile training models, that operationalise these resilience requirements via revised STCW competencies and specialised training and certification pathways. Aligning maritime education and training programs, with the highly demands of cyber-physical nuclear propulsion ensures that personnel are capable of sustaining safe operations even under degraded or adversarial conditions.

Taken together, this integrated approach— secure technical architecture, organisational resilience, and human capability—defines a coherent pathway for managing cyber-physical risks in nuclear-powered merchant vessels. By embedding cybersecurity into both engineering design and governance structures, and by reinforcing these measures through targeted training and certification, the maritime sector can responsibly harness the decarbonisation potential offered by new generation fourth Small Modular Reactors. Cyber-physical risk in nuclear shipping thus emerges not as a limiting factor, but as a defining frontier for the next generation of maritime safety and regulation in the digital era.

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Observed Performance of Situation Awareness and Perceived Workload in Nautical Simulation: A Pilot Study

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Abstract: Although situational awareness and workload management are important for safe maritime navigation, there is little research using objective technological methods to examine how senior naval officers develop situational awareness and manage workload when assuming command. There is a particular lack of research on highly certified officers in realistic but controlled bridge conditions. Therefore, pilot studies using tools such as eye tracking and workload analysis are needed. This pilot study investigated differences in observed performance related to situational awareness and perceived workload by combining eye-tracking data, behavioural observation, and post-exercise subjective workload assessment. The study involved six participants holding the highest maritime certifications, Chief Officer and/or Ship Master. All were familiar with the bridge equipment and environment and provided informed consent before the experiment. In the experimental scenario, the officer of the watch (OOW) initially directed the ship's navigation while the participant, acting as master, observed. After gathering the necessary information and developing situational awareness, the participant assumed the navigational watch and continued to steer the ship. To ensure identical initial conditions, the OOW always followed the same procedure until formally relieved. During the exercise, data were collected on gaze direction towards predefined areas of interest, bridge communication, behaviour, and reactions. Afterward, participants completed the NASA Task Load Index (NASA-TLX) questionnaire to assess perceived workload. The results indicate the need for further research, particularly on workload assessment using advanced technological methods to be further developed within the MASTERS project

Keywords: nautical simulator; eye tracking; situational awareness; perceived workload

1. Introduction

Safe navigation is largely dependent on the ability of the officer of the watch (OOW) to effectively perform duties defined within the framework of the International Maritime Organization (IMO) and the STCW Convention (IMO, 2017). These duties include continuous monitoring of the navigation environment, systematic collection of relevant information, its proper interpretation, and timely decision-making to ensure the safety of the vessel, crew, and environment. The increasing complexity of modern bridge systems, together with higher traffic density in certain navigational areas, further emphasizes the importance of human performance in maintaining safe navigation.

Despite continuous improvements in maritime technology and regulatory frameworks, maritime accidents remain a significant concern. Analyses of such accidents show that deficiencies in situational awareness (SA) are among the key contributing factors (Gommosani, Turan and Kurt, 2021). According to the European Maritime Safety Agency (EMSA) Annual Overview of Marine Casualties and Incidents, more than 75% of marine accidents are associated with the human element. This indicates that human actions, decisions, or behaviors play a significant role in the occurrence of such incidents (EMSA, 2025).

More detailed investigations into accident causation reveal that maritime accidents are rarely the result of a single error, but rather occur as a consequence of a chain of interacting failures across multiple levels (Hasanspahić et al., 2021). Their analysis, based on the HFACS-MA framework, emphasizes the importance of both individual conditions and higher-level organizational influences in accident causation. Similarly, the Bayesian network model developed by Vojković et al. (2021) demonstrates that maritime accidents arise from

complex interactions among multiple interdependent factors, confirming the multifactorial nature of maritime risk.

Within this context, SA represents a central concept in understanding human performance in navigation. The widely accepted theoretical model proposed by Endsley (1995) defines SA as a three-level process consisting of perception, comprehension, and projection. In maritime applications, maintaining an adequate level of SA is essential for safe watchkeeping (Jaram et al., 2021). However, various operational factors can influence SA, including the presence of alarms and alerts, which may either support or hinder operator performance depending on their design and frequency (Maglić and Zec, 2020). In addition, cognitive load and stress have been identified as key elements affecting human performance, with measurable impacts on attention distribution and decision-making processes (Žagar et al., 2020).

In recent years, eye-tracking technology (ETT) has emerged as a valuable tool for objectively assessing human behavior and attention in maritime environments. By capturing gaze patterns and visual focus, ETT enables detailed analysis of how navigators interact with bridge equipment and their surroundings. Early studies demonstrated the potential of eye-tracking in maritime usability research (Hareide and Ostnes, 2017), while later work further explored its application in real-time navigation and high-speed craft operations (Odd Sveinung Hareide, 2019). Additional research has investigated the usability of electronic navigation systems (Arslan, Atik and Kahraman, 2021), as well as broader applications of ETT in shipboard operations (Uflaz et al., 2023).

More recent studies have expanded the methodological approaches to analyzing eye-tracking data. Petrović and Vujičić (2025) explored discrepancies between perceived and actual navigational performance, highlighting the potential of ETT in identifying hidden aspects of operator behavior. Furthermore, novel approaches such as gaze similarity analysis have been proposed as a means of evaluating cognitive processes and performance (Bin Kamarumtham and Murai, 2025), while systematic reviews confirm the growing importance and applicability of ETT in maritime research (Bin Kamarumtham et al., 2026).

Nevertheless, the application of ETT in dynamic simulation environments presents several challenges. These include technical limitations, data interpretation issues, and the potential influence of wearable devices on participant behavior, particularly in situations involving movement and interaction with bridge equipment (Petrović and Vujičić, 2024). Such limitations highlight the need for carefully designed experimental methodologies and further validation of results.

In light of the above, this pilot study aims to investigate differences in observed performance related to situational awareness and perceived workload by combining eye-tracking technology (ETT), structured observations of participants' behaviour and bridge communication, and post-exercise subjective workload assessment. The study contributes to a better understanding of human performance on the navigational bridge and provides a methodological basis for further research within the MASTERS project framework.

2. Methodology

2.1. Study Design and Participants

This pilot study was conducted at University of Dubrovnik on the Kongsberg Polaris bridge simulator approved by Det Norske Veritas (DNV) to analyse human performance in a controlled navigational scenario. The study involved a purposive sample of six Croatian participants holding Chief Officer and/or Master licences, all with prior experience in bridge operations and nautical simulators. The limited sample size reflects the exploratory nature of this pilot study and was considered appropriate for evaluating the proposed experimental methodology rather than for drawing generalisable conclusions. Participants' background characteristics are presented in Table 1.

Table 1. Respondents characteristics

	AGE	SEA EXPERIENCE	DIFFERENT NUMBER OF SHIPS
P1	30	5	4
P2	31	8	6
P3	47	15	8
P4	48	24	28
P5	49	25	14
P6	48	10	16

Prior to participation, all candidates were informed about the study and signed a Participant Consent and Waiver Form related to the use of eye-tracking equipment and data collection. After completing the exercise, participants completed the NASA Task Load Index (NASA-TLX) questionnaire to assess their perceived workload.

2.2. Experimental Scenario

The complete simulation scenario lasted approximately 20 minutes and was designed to simulate a realistic and dynamically developing traffic situation in the Strait of Gibraltar, characterized by high traffic density and complex navigational conditions. The scenario design was based on previous simulator-based maritime research and established approaches to navigational risk assessment and decision-making (Vujičić et al., 2017; Brcko et al., 2021; Mohović et al., 2021; Petrović, 2025).

During the initial phase, the role of the officer of the watch (OOW) was performed by one of the researchers, following a predefined and consistent navigational procedure to ensure identical initial conditions for all participants. Upon entering the bridge, participants assumed the role of the Master and were provided with a standardized verbal briefing regarding the traffic situation.

The scenario included multiple vessels, with two key targets representing potential collision risks: one approaching from the port side and one from the starboard side. The OOW maintained a consistent interpretation of the situation, indicating that the port-side vessel would alter course, as typically expected. However, the evolving situation was designed to challenge this assumption, progressively reducing the available time for safe decision-making.

Participants were expected to assess the situation, achieve situational awareness (SA), and, based on their own judgement, take over the con when they considered intervention necessary to ensure safe navigation and collision avoidance. Consequently, the timing of assuming the con was not predefined but depended on each participant's assessment of the developing traffic situation. In the context of this pilot study, situational awareness was not measured directly using a dedicated SA assessment instrument. Instead, participants' situation assessment was interpreted through a combination of complementary indicators, including eye-tracking measures of visual attention, behavioural observations, bridge communication, and operational performance, reflected in the timing and appropriateness of assuming the con.

2.3. Data Collection and Analysis

During the experiment, data were collected from multiple sources, including ETT recordings, behavioural observations and bridge communication, and post-exercise subjective workload assessment. Behavioural observations focused on participants' responses to the developing navigational situation, including their interaction with the OOW, bridge communication, timing of assuming the con, and execution of navigational actions. These observations were used as complementary qualitative indicators to support the interpretation of eye-tracking data and operational performance.

ETT data were obtained using Tobii Pro Glasses 3 (Tobii AB, 2023a) and analysed using Tobii Pro Lab software (Tobii AB, 2023b), allowing assessment of gaze behaviour and attention distribution across predefined areas of interest.

Following the simulation, participants completed the NASA Task Load Index (TLX) questionnaire. The NASA TLX is widely regarded as the gold standard for subjective workload measurement across a broad range of applications (NASA, 2026). The instrument was originally developed by Hart and Staveland (1988) and has since been extensively applied in scientific research (Hart, 2006), including studies conducted in high stress environments (Wu et al., 2024).

Each participant provided one rating (0-100) for each of six NASA-TLX dimensions. Group-level subscale scores reported in this study represent the mean of participants ratings for each dimension.

The collected data were analysed in two segments: (i) eye-tracking data, focusing on gaze distribution and attention allocation, and (ii) questionnaire data, correlation analysis of perceived workload and respondent's demographic variables. Questionnaire data were analyzed using IBM SPSS Statistics 29 (SPSS Inc., Chicago, USA).

3. Results

3.1. Eye tracking data

The analysis of ETT data was conducted for all six participants using heat map visualisations and quantitative distribution of gaze across predefined Areas of Interest (AOIs).

The summary heat map (Figure 1) confirms general trend, showing a clear concentration of gaze in the outside view area (window). This is expected in dynamic collision avoidance scenarios, where continuous monitoring of surrounding traffic is essential for maintaining situational awareness.



Figure 1: Eye tracking heat map, Summary

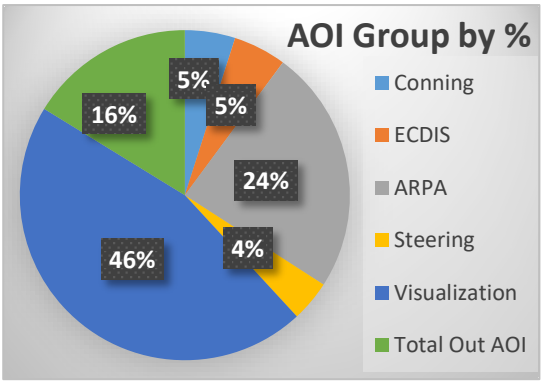


Figure 2: Percentage according AOI

The quantitative analysis of gaze distribution across AOIs (Table 2) reveals that, on average, the highest percentage of attention was allocated to:

- Visualisation (outside view): 45.63%
- ARPA: 23.98%

A notable portion of gaze was also recorded in the "Total outside" AOI (16.24%), which represents visual attention directed outside the predefined Areas of Interest used in this study. This category may include gaze directed towards non-instrument areas of the bridge, bridge team interaction, communication with the OOW, or other contextual elements that were not classified as predefined AOIs. Lower attention levels were observed for:

- ECDIS: 5.20%
- Conning: 4.93%
- Steering: 4.02%

These results indicate that participants predominantly relied on direct visual observation supported by radar (ARPA), while electronic chart systems and navigational control interfaces were used to a lesser extent.

Table 2. Observation AOI as per respondents

AREA OF INTEREST	CONNING	ECDIS	ARPA	STEERING	VISUALISATION	TOTAL OUTSIDE
P1	2.40%	5.36%	32.90%	5.42%	39.99%	13.94%
P2	8.46%	2.52%	19.16%	4.97%	44.21%	20.69%
P3	4.12%	11.52%	38.46%	0.01%	29.93%	15.95%
P4	5.37%	4.00%	19.63%	2.17%	48.32%	20.51%
P5	1.35%	2.25%	10.74%	7.07%	64.57%	14.02%
P6	7.85%	5.53%	23.00%	4.49%	46.78%	12.35%
MEAN (AVERAGE)	4.93%	5.20%	23.98%	4.02%	45.63%	16.24%
MIN	1.35%	2.25%	10.74%	0.01%	29.93%	12.35%
MAX	8.46%	11.52%	38.46%	7.07%	64.57%	20.69%

Although general trends were consistent, some variability between participants was observed. For example:

- Respondent 5 demonstrated the highest reliance on visualisation (64.57%), suggesting a strong preference for external observation.
- Respondent 3 showed the highest attention allocation to ARPA (38.46%), indicating a more instrument-based approach.
- Differences in ECDIS usage were also evident, with values ranging from 2.25% to 11.52%.

Such variability may suggest possible differences in individual information acquisition and processing strategies. However, given the exploratory nature of this pilot study, further investigation involving a larger sample and additional performance indicators is required before drawing broader conclusions. An important observation relates to the proportion of gaze directed outside the predefined AOIs. Although such gaze does not necessarily indicate loss of attention or situational awareness, prolonged periods outside task-relevant information sources may reduce the opportunity to detect changes in the navigational situation. Therefore, this finding should be interpreted cautiously and may provide a useful basis for further investigation of attention allocation and bridge team interaction. The observed dominance of visual attention directed towards the external environment aligns with the requirements of maintaining situational awareness in complex navigational scenarios. Continuous monitoring of surrounding traffic is essential for perception and comprehension of the situation, as defined in situational awareness models.

At the same time, the significant use of ARPA indicates reliance on technological support for target tracking and collision risk assessment, highlighting the interaction between human perception and navigational systems.

The relatively low attention allocated to ECDIS, conning display, and steering controls may suggest that these elements were used selectively, primarily for confirmation rather than continuous monitoring. In some cases, minimal attention to steering may also indicate reliance on the helmsman for execution of manoeuvres, which opens additional considerations regarding monitoring of control actions.

3.2. Questionnaire data

In order to examine the meaningful relationships between respondents' demographic variables (age, sea-time experience, and number of different ships sailed) and their perceived levels of workload, Spearman's rank-order correlation analysis was employed, as the data did not meet the assumption of normality. Spearman's correlation operates on the ranked values of the scores rather than relying on a normal distribution, making it an appropriate and reliable statistical method for the characteristics of this dataset

Table 3 presents descriptive statistics (means and standard deviations) together with exploratory correlation coefficients between the variables included in the analysis. Owing to the pilot nature of the study and the limited sample size ($n = 6$), these correlations should be interpreted as preliminary observations intended to identify potential relationships for future investigation rather than to establish generalisable associations. Within the observed sample, perceived mental demand showed a strong positive correlation with physical demand ($r = 0.96$, $p < 0.01$) and temporal demand ($r = 0.93$, $p < 0.01$). A strong positive correlation was also observed between physical demand and temporal demand ($r = 0.88$, $p < 0.05$). Furthermore, perceived performance showed a strong negative correlation with frustration ($r = –0.91$, $p < 0.05$).

Table 3. Means, standard deviations and correlations between used variables

	M	SD	1.	2.	3.	4.	5.	6.	7.	8.	9.
1. Age	42.17	9.07	-								
2. Sea Service	14.50	8.41	0.77	-							
3. No. of Ships	12.67	8.82	0.69	0.72	-						
4. Mental Demand	40.00	31.62	0.33	0.44	0.39	-					
5. Physical Demand	40.00	27.57	0.37	0.35	0.33	0.96**	-				
6. Temporal Demand	40.83	30.40	-0.02	0.19	0.24	0.93**	0.88*	-			
7. Performance	76.67	30.11	-0.61	-0.75	-0.13	-0.29	-0.29	-0.20	-		
8. Effort	55.00	21.68	0.14	0.36	0.27	0.70	0.77	0.75	-0.28	-	
9. Frustration	31.67	19.41	0.45	0.58	-0.03	0.55	0.56	0.34	-0.91*	0.45	-

* Correlation is significant at the 0.05 level (2-tailed). ** Correlation is significant at the 0.01 level (2-tailed).

4. Discussion and Conclusion

Technical and non-technical skills are evaluated during exercises. Among these, effective visual observation of surrounding traffic requiring the maintenance of a proper lookout in accordance with the International Regulations for Preventing Collisions at Sea (COLREGs) is considered one of the most critical skills expected from participants.

It also represents an important source of information when assessing situational awareness in navigational practice.

In the present study, eye-tracking technology provided an objective measure of visual attention distribution, while subjective workload was assessed using the NASA-TLX questionnaire. Situational awareness, however, was not measured directly using a dedicated SA assessment instrument, but was interpreted from a combination of visual attention patterns, behavioural observations, bridge communication, and participants' operational performance during the simulation. Situational awareness is typically conceptualized across three levels: perception, comprehension, and projection, as defined by Endsley's SA Model. Although these levels can be partially interpreted through observation of participant behavior and decision-making, such methods are inherently limited in capturing the underlying cognitive processes.

To address these limitations, ETT is proposed as a complementary assessment tool, enabling more detailed insight into visual attention patterns and supporting a more objective evaluation of situational awareness in maritime contexts.

The results of the eye-tracking analysis indicate that participants predominantly relied on direct visual observation of the external environment, supported by radar-based information (ARPA), while other navigational systems such as ECDIS and conning displays were used to a lesser extent. This behaviour is consistent with the requirements of maintaining situational awareness in dynamic navigational conditions.

At the same time, differences between participants suggest variability in individual strategies, particularly in the balance between visual observation and instrument-based monitoring.

A notable finding relates to the proportion of gaze directed outside relevant Areas of Interest (Total outside AOI), which may indicate temporary shifts of attention away from task-relevant information. Although this does not necessarily imply a loss of situational awareness, it highlights the importance of attention management in complex bridge environments.

The relatively low attention allocated to steering and control interfaces may also indicate reliance on other crew members for execution of manoeuvres, raising considerations regarding monitoring of control actions.

The correlation analysis indicated strong statistically significant relationships among the workload variables: mental demand with physical and temporal demand, and physical with temporal demand. Additionally, higher performance was strongly associated with lower frustration. On the other side, the analysis showed no statistically significant relationships between respondents' demographics and workload variables. However, it should be emphasized that this study is a pilot investigation with a limited sample size. Therefore, the results should be interpreted as preliminary. Future studies should investigate the relationship between objective eye-tracking indicators and subjective workload measures using larger participant samples. The incorporation of additional eye-tracking metrics, such as fixation duration, fixation count, scan path analysis

and transition analysis, may provide a more comprehensive understanding of navigational behaviour and situational awareness. Nevertheless, the findings provide a meaningful basis for further research, particularly in exploring the relationship between visual attention, situational awareness, and perceived workload within more complex and realistic operational scenarios.

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The Uptake of Digital Solutions in Container Liner Shipping

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Abstract: The digital transformation of an established industry represents a complex and multifaceted challenge. This is particularly true for industries characterized by traditional practices, predominantly manual operations, and globally dispersed stakeholders. Nevertheless, incremental improvements can contribute substantially to the overall digital transformation process. Therefore, this paper will address the uptake of a digital solution for a sub-task in global shipping: Berth Alignment.
Developing a digital solution to replace a manual process is one step of the transition. The second step is implementation on a large scale. It will be shown that the uptake, also known as digital adoption, of a digital solution by the stakeholders can be influenced and increased when drawing attention to technology, organization, and the surrounding environment.
The paper first reviews the current state of research on digitalization in container liner shipping before examining berth alignment and its operational relevance. Next, berth alignment is explained, and its importance described, which grew over the last years under the pressure of the Covid-19 crisis and lack of resources in the maritime world. This is followed by an introduction to the concept of digital adoption.
In this paper, one part of a larger research setting, will be demonstrated, representing an exploratory qualitative research study. The analysis includes several interviews with early adopters of the software as well as interviews with industry experts and leaders. Some uptake initiatives will be derived from the Technology-Organization-Environment (TOE) Framework by (Tornatzky et al., 1990). This research is needed as there is very little work done on digital adoption in traditional environments with mainly manual tasks. This study addresses a gap in the existing literature, as research on digital adoption in traditional industries characterized by predominantly manual processes remains limited. Furthermore, the global implementation of digital solutions introduces additional complexity, as cultural differences may influence users' acceptance of new technologies and changes to established work practices.
Conclusively, this study works out some favorable conditions to increase the digital adoption of a new software and further develops recommendations for an even more successful and sustainable implementation of the new digital berth alignment software and process.

Keywords: Digitalization; Transition; Transformation; Container Shipping; Change Management

1. Introduction

Maritime shipping constitutes one of the fundamental pillars of global trade while remaining a traditionally organized industry. Structures have grown over hundreds of years, bringing countries, cultures, and companies together. Vessels connect ports, terminals and eventually customers with sellers. Several cargo carriers work together with a large number of worldwide terminals, making this system robust but also complex.

At the same time, shipping is faced with consistent change and unpredictability. Recent disruptions, including the COVID-19 pandemic and the blockage of the Suez Canal, have highlighted the vulnerability of global maritime supply chains. But even the day-to-day operation needs constant readjustment as vessels omit terminals, perform a change of rotation, react to bad weather or damages of quays, or delays of foregoing vessels. Thus, long term agreements about port calls have to be revisited and modified accordingly to these short notice changes between terminals and carriers. Individual negotiations for the berth alignment are needed, requiring data and information exchange between the involved parties to act agile and responsive under time pressure (Rosenberg, 2020).

The allocation of berth space between terminal operators and shipping lines continues to rely heavily on manual coordination, including unstructured email communication, spreadsheets, PDF documents, and

telephone conversations. Further, there have been no standards for the exchange of data or even for the terminology. Conclusively, berth alignment is difficult while it also is the basis of a well-working supply chain.

To digitize and improve the berth alignment, tools are available. However, the successful use of a digital berth alignment tool requires a collective use between terminal and carrier, training of personnel and a mindset-change from traditional formats to a computerized process. This paper will give an overview of digitalization in maritime operations as well as crucial actions to increase the uptake of digital tools.

2. Background

2.1. Digitalization in Container Shipping

Compared with industries of similar economic importance, the maritime shipping sector continues to rely on a comparatively high proportion of manual processes. Little research and examination have taken place in the field of digitalizing shipping operations (Brunila et al., 2021). This is even more interesting when looking at the statistics for global trade: The logistics sector today is one of the greatest data consumers and generators worldwide. Driven by globalization and digitalization, data has become a strategic resource for value creation and operational decision-making. (Linnhoff-Popien et al., 2018). Consequently, the maritime industry is currently not using its full potential when it comes to the implementation of digital solutions around shipping. "Leading shipping companies are investing heavily in smart assets … to digitalize their fleet, operations and administration … collaborating to define enabling technologies, including specifications and requirements for Internet of things (IoT) communication and data exchange interfaces." (Becha et al., 2020) Data exchange and data exchange interfaces are a challenge in this industry, with its vast number of participants ranging from international and data-driven companies to local actors with limited IT knowledge and resources. Dong-Ping Song calls it the "long-lasting fragmentation issue in shipping supply chain". (Song, 2023) Further, maritime logistics is described by network-centric behavior, with around 40 independent actors to be engaged in port-to-port or door-to-door voyages. This demonstrates the lack of seamless coordination and indicates costly manual processes (Lind et al., 2020; Raza et al., 2022). The lack of international cooperation could also be seen when TradeLense by Maersk came to a halt in 2023. Other characterizations about the industry shared by multiple researchers include heterogeneity, conservativeness, risk-aversion, volatility, and lack of transparency (Stölze and Lieb, 2012; Song, 2023; Freitag et al., 2021). Conclusively, these traits are leading to non-standardized data and non-interoperable technologies, which cause severe consequences and inefficiencies with an impact on businesses and operations. Delays and time-loss resulting from insufficient transparent data sharing, deficient communication, and unaligned processes cause strains on the quality and performance in the maritime transport but also on global supply chains as a whole. (Notteboom et al., 2022)

2.2 Berth Alignment

A critical moment in the global supply chain is the berthing of the vessel at a terminal. Seaports with their terminals are fundamental nodes and value-driving elements in maritime transport and are responsible for numerous logistic services (Herz and Flämig, 2014). Thus, there is a substantial amount of data that needs to be exchanged between several actors before and during the approach of the quay wall. Generally, container traffic is known to follow a predefined schedule including recurrent port visits. In the past and in theory, this has enabled carriers and ports to plan and arrange berths by pre-allocating vessels at dedicated berths, based on contracts and agreements. This operational planning and effective utilization of resources, including berths and cranes, is especially crucial due to their high investment costs and finite attributes (Lee and Meng, 2014; Lind et al.,2020).

However, the long-term berth alignment can be interrupted and often must be readjusted. On one hand, the vessel can cause the interruption: vessel arrivals can be late caused by weather conditions, delays in previous ports, canal closures, operational detours, or other voyage disruptions. This explains the declining trend of schedule reliability from the vessel-side, with an especially deep dip for the Covid-years. (Kircher, 2023)

On the other hand, the terminal can cause a diversion from the originally agreed berth time: the berth can still be occupied by a previous vessel due to yard congestion, personnel could be insufficient, cranes can be out of operation, or a previous vessel operation could be delayed. Port congestion is one indication of terminal delays being directly correlated to the Berth Allocation Problem (BAP), indicating the misfunctioning management of quaysides and carrier dependency since vessels are subject to a limited number of berths (Song, 2023). Under all and any of those circumstances, a new berth alignment must happen. In other words, the terminal and the carrier have to agree on a new time when the vessel could dock at an available berth. For this

matter, information about estimated arrival time (when could the vessel be there), estimated availability of berth (when would the berth space be available), and estimated cargo volume (how long will the vessel stay potentially) has to be exchanged at a minimum. In several locations additional information is crucial, such as air draft and draft of the vessel. The exchange of this data is currently not standardized nor even the definitions of these data points. However, the nonprofit association "Digital Container Shipping Association" (DCSA) launched in 2019 and embodying 9 major carriers, which presently account for approximately 70% of the global container trade (Notteboom et al., 2022), works towards standardization throughout the maritime industry starting from the view of container carriers. With their time stamps and their time stamp definitions, the DCSA aims at better cooperation in the industry by allowing the sharing of precise data across the globe. Their standpoint is that berth alignment should be digitalized to connect carriers with terminal networks around a real-time schedule, based on standardizations established by the Digital Container Shipping Association (DCSA)- and thus implemented by all involved container carriers. Standardization proves to be the fundament of digitalization.

Consequently, close collaboration and exchange of transparent and early information seems to be key to an optimization of berth alignment processes, especially when dealing with increasing uncertainty and tight berth lineups. Sharing information timely and accurately with precise meaning understood by all parties is crucial to improve the port-stay in a terminal and to reduce waste.

2.3 Digital Adoption

Digital adoption refers to the circumstance where digital tools are utilized as intended and leveraged to their fullest extent (Keyhani et al., 2022). Thus, digital adoption serves as the basis to applying digital tools and processes for digitalization. Despite the innovativeness and sophisticated capabilities of digital tools and platforms, these are only value-adding once the potentials are realized by user adoption and sufficient utilization rates (Becha et al., 2020; Lind et al., 2020). Ultimately, the success of a digital solution depends on its effective adoption and sustained use by end users.

However, changing the behavior of the user towards the application is a challenge due to several aspects: (1.) The steep learning curve required in the uptake of digital solutions can cause psychological hurdles (HBR, 2021). (2.) Unwillingness and lack of enthusiasm to change are encountered frequently, fed by fear of the unknown or for foreseen potential increases in effort (Lind et al., 2020). (3.) Resistance can also be caused by ignorance or negative attitudes toward digitalization, including the fear of job loss (Brunila et al., 2021, Raza et al., 2022). (4.) Rejection of digital adoption worsens with missing leadership or management, as those circumstances influence employee's values, attitudes, and behaviors. (5.) Specifically conservative and traditional mindsets increase barriers to understanding the necessity to digitally adopt due to missing knowledge about the added value and opportunities available (Balci and Surucu-Balci 2021; Gavalas et al., 2022).

Therefore, the success of digital adoption challenges especially traditional shipping organizations to identify human capital as the crucial asset (Rosenberg, 2020).

Efficiency gains through digitalization and subsequent digital adoption are substantial areas with predominantly routine tasks. Thus, the maritime transport industry with its many conventional and analog labor tasks, creating information flows for international logistics, could gain significant efficiency advantages by successfully implementing digital solutions (Song, 2023) quicker and more extensively. Unsurprisingly, productive shipping companies are recorded to be leading in gaining advantages from adopting innovative digital skills (Gavalas at al., 2022). A cloud-based software allowing terminals and carriers to digitally agree a berthing window as core function will be investigated, enriched by further information such as live position of the vessel, previous and following destination, container move counts, drafts and air drafts, etc., which has recently started to be rolled out and implemented at various regions and terminals worldwide in the global maritime terminal network. Not without resistance.

In this research paper the global digital adoption of the digital berth alignment software will be investigated and measures will be developed to improve the uptake. This is needed as currently there is no analysis regarding the implementation of a digital tool to globally transform an operational process, particularly not within the shipping industry.

3. Methodology: Qualitative Analysis - Interviews

The interviewee selection is based on a non-probability sampling scheme: The selection includes an element of subjective judgment alongside the features of purposive heterogeneous sampling to achieve a variable and comprehensive scope of perspectives (Saunders et al., 2019). This study was conducted early on

in the onset of software rollouts and implementation; thus, experiences and research participants were limited while highly important for the further project scope and success. In a global operation uptake of new digital solutions varies widely and may be influenced by culture. To get the full global overview even in this early stage, one person for each geographical area was included, as well as additional global stakeholders of the project. Due to the earlyness of the study, the amount of possible interview partners was restricted, and thus could not include additional factors such as gender, age, work experience, education, etc.

The small sample size of seven semi-structured one-to-one expert interviews was determined within a larger research project (expanded by quantitative research questions, which are not part of this research paper), proportional to the study's scope. The interview questions were provided to the participants in advance to ensure the preparation of interviewees and enhance the interview flow. Open interview questions shall encourage extensive answers and reveal true insights (O'Gorman and MacIntosh, 2015; Saunders et al., 2019). The interviews were conducted via Microsoft Teams owing to geographical dispersion and resource constraints. (O'Gorman and MacIntosh. 2015; Saunders et al., 2019). The analysis of the qualitative data follows an inductive approach, identifying themes by studying raw textual data (Saunders et al., 2019). Mayring's summarization format is applied to condense the raw textual data into a more focused format (Mayring, 2015). This data is then analyzed by thematic content analysis, which is a "method for identifying, analysing, and reporting themes within data" (O'Gorman and MacIntosh, 2015).

Conclusively, the method of expert interviews has been established applicable in an exploratory qualitative research design for studies in the shipping industry, yielding valuable, revelatory, and rich data (Raza et al., 2022). The overarching objective of the expert interviews is to collect information and perspectives about the implementation of a berth alignment software tool with respect to a Digital Berth Alignment (DBA) process. The ambition is to define and elaborate on the role or influence of digital adoption. The names of the interviewees have been anonymized, and the interviewees are now solely identified by function.

4. Findings

4.1 Implications of a digital tool on the berth alignment process

The efforts to digitize the berth alignment process surfaced right before the Covid-19 crisis. Manual and intransparent procedures around the berthing, varying from terminal to terminal, became visible under pressure and revealed the limitations and inadequacy of the established traditional alignment process. At the carriers' side, these circumstances pushed the objective to transition to the DBA process by implementing a digital berth alignment software (Global Operations Head, personal interview, 2023). Additionally, apart from the turbulence caused by Covid-19, the traditional berth alignment process may be the source of multiple operational challenges, such as manual and time-intensive tasks, miscommunication, unproductive intermediates, or siloed procedures (Manager North America, personal interview, 2023; Manager Middle East, personal interview, 2023; Manager South Europe, personal interview, 2023). With an agreed berthing process established by the carrier, the process is bound to be standardized across the world, creating benefits for the carrier but also to the industry by increasing situational awareness, timely appropriate actions, and structured correspondence (Manager North America, personal interview, 2023; Manager South Europe, personal interview, 2023). Further, the digital process is also believed to reduce about 80 percent of the manual tasks, thus creating higher productivity (Manager Asia, personal interview, 2023). While these numbers are not yet proven, a more general statement by participating entities is that individual phone calls and emails have greatly reduced, also reducing the need to respond to individual requests.

However, while the positive aspects seem to outweigh the efforts of introducing the software, other carriers are allegedly not catching on as quickly to standardize and digitize their berthing processes. While they undoubtedly invested in digitalization and innovations (Global Operations Head, personal interview, 2023; Software Provider Key Account Manager, personal interview, 2023), a focus point of these efforts is on commercial improvements and monetary gains, not on process optimization. Further, some carriers in the market carry an extensive network of dedicated terminals and larger terminal shares respectively, so the need to create a better operational alignment may not be a main concern.

Digital initiatives at the carriers side mainly take place in the commercial business and projects, such as an online pricing tool (Global Operations Head, personal interview, 2023), with the digital berth alignment tool filling a gap in the communication between service provider and the carrier on the operational side of the business. The degree of digital adoption within the users varies based on individual responsibilities and experiences with different software and business applications. Personal interest and attitudes also play an

important role in the adoption of new digital technologies. (Manager Asia, personal interview, 2023; Manager South Europe, personal interview, 2023; Manager Middle East, personal interview, 2023).

The carrier has been introducing a number of digital tools to all fields, also establishing the need for change and digital uptake in its corporate strategy specifically defining a global digital company culture (Global Operations Head, personal interview, 2023; Manager South Europe, personal interview, 2023). The Covid-19 crisis accelerated this aim not only in the commercial area: "Responsibilities related to berth operations require and embody much more data now… digital adoption focuses on tool incorporation for work success, efficiency, and error reduction" (Manager Middle East, personal interview, 2023). The interviewed users of the digital berth alignment platform demonstrated a clear understanding of its operational benefits and perceived value, and are aligned with the digital evolution of the maritime industry.

4.2 Challenges in the implementation

With interviews in each geographical region, challenges and hurdles in the uptake of the new software solution and the new digital berth alignment process are discussed. Using this exploratory research method, the following several challenges were identified: a) The shipping industry is very diverse and, in some instances, benefits from intransparent data and asymmetric information. Sharing information live and transparent with other industry participants is not ingrained in the maritime industry. Creating common ground and trust is thus fundamental for digital exchange of data. b) The berth alignment process is locally driven and depends on the engagement of several and diverse stakeholders. While the agreement of terminal and carrier is the cornerstone in this process, port authorities, agencies, agents, tugboats, pilots, etc., are involved and create a vast variety of information and actions. Standards for this process are lacking. On top, information can change very rapidly, which requires additional collaboration, sometimes on short notice. Streamlining and digitizing this process is thus a challenge. c) While the streamlining and digitizing of the process is a challenge (as described in point b)), the uptake of a digital solution is another critical challenge. As pointed out, the berth alignment is arranged mostly local with a lot of human interaction between all parties. Transitioning from an inherently manual process to a digital process involves openness to the digital platform and to a new way of alignment. Resistance to organizational change remains particularly pronounced in traditionally structured industries such as maritime shipping. d) To increase the chances for change, the process adherence has to be followed while also encouraging to use the digital tool continuously. Long-term efforts may be required to displace the manual work. e) To increase the efficiency of the digital berth alignment process and to keep personnel engaged, manual input should be reduced to a minimum, while the application should automatically show and distribute crucial data. Providing mobile access to operational data facilitates the timely communication of operational changes and improves information sharing among stakeholders.

Conclusively, several challenges became apparent throughout the interviews, highlighting how difficult the uptake of a digital software solution can be. Not only has the platform been built accurately and the employees have to be trained on it accordingly, but the general larger environment also plays a significant role. To digitize a long-standing traditionally manual process into a transparent, sustainable, and digital/automated process while involving personnel seems to be more difficult than designing the software in the first place.

4.3 Recommendations for actions and improvements

To develop suitable actions for the challenges laid out in the foregoing chapter, the Technology-Organization-Environment (TOE) Framework by (Tornatzky et al., 1990) will be applied. The TOE framework consists of three key aspects and covers internal as well as external factors when introducing novel technologies and digital adoptions. By applying, several actionable recommendations can be derived from the TOE framework to address the challenges. A summary of the findings is shown in Table 1.

Technology (T):

- Creating a software that reflects the current manual process increases **familiarity** with the tool. At the same time, the digital software also needs to be able to reflect digital standards from the industry in wording and functionality. Finding a right balance between the traditional process and the future way forward is crucial and difficult at the same time. However, it will make the software last beyond the manual input and keep involved parties on track. (b)
- **Continuous enhancement** and rectifications of the software is a way to keep the users engaged and trusting in the tool. Further developments such as a mobile application, extensions such as the vessel tracker, etc. make the tool better and more usable over time, increasing the use cases. (c)

- **Extended automation** from the terminal and carriers' side will improve the accuracy of the data shared. Optimizing the automated data flow decreases the need for manual data input, which frees up the employees, while also creating a streamlined data exchange. (e)

Organization (O):

- When aiming to increase digital adoption, employees must receive **adequate training** on new technologies. Creating a trustful relationship between employees and employers can help to transition from one technology to another without losing engagement. Reducing resentment while increasing excitement about a new digital tool can support the uptake, especially if the software is user-friendly. Additionally, external users of the software from the terminals should experience the same treatment, guiding them through the training and involving them in the journey. (a, b, and c)
- The impact of the new software tool for digital berth alignment needs to be evaluated and the results shared transparently, e.g., with **KPIs**. If the use case as well as the benefits of the value-adding transition are clearly laid out and communicated throughout the organization, an identification with the new process can grow. This can help to support the uptake in other regions and departments but also within other stakeholders. (d)

Environment (E):

- With the implementation of the new software, a first significant step is done towards an open and **transparent data exchange** between stakeholders in a port. By including parties beyond carriers and terminals, a relationship can be created, thriving from benefits the open data transmission can initiate. Open information and using industry standards allow for leaner planning avoiding waste and inefficiencies for all participants. (a)
- Several other carriers and terminals need to join this progress. With a **critical mass**, the whole industry can be transformed into the future, generating savings by eliminating waste. This can not only support cost savings, but also supports the environmental efforts the maritime industry is currently driving forward. (a)
- Gains from the software implementation need to be communicated towards the larger industry to create **awareness** and knowledge. Higher visibility of the efforts and realized impacts could convince other industry participants to reach out and transform themselves. (a)
- Traditional and intransparent processes need to be addressed in the shipping industry. Using **common standards** (DCSA) can support this process. Other industries are ahead of the shipping industry in this matter, and the maritime industry has yet to catch up. (b and e)

Table 1: Challenges and solutions based on TOE framework, summary. Source: (Kircher, 2023), adapted

#	Challenge	Solution(s)	
a)	Shipping Industry Environment	• Adequate training (O) • Transparent data exchange (E)	• Critical user mass (E) • Industry awareness (E)
b)	Focus on Berth Alignment	• Familiarity of the process (T) • Adequate training (O)	• Common standards (E)
c)	Digital Adoption	• Continuous enhancement (T)	• Adequate training (O)
d)	Performance/Development Monitoring	• Evaluation via KPIs (O)	
e)	Technical Constraints	• Extended automation (T)	• Common standards (E)

5. Conclusions, Limitations and Further Research

5.1 Conclusion

The high level of efforts to transform to a digital company with digitized services over the last years can be seen as a benefit when evaluating the digital adoption in regards to the new digital berth alignment tool. Focus and action on innovation and technology has increased awareness and ability for the carrier's daily

software users to understand the positive impact on the business as well as eased the transition from a manual process towards a digital and automated process.

At the same time, external users represent a more diverse group with different levels of training and comprehension of the positive effects of transparent and timely data exchange in their locations. Different levels of digitalization from the terminal side can hinder the uptake of the technology, while the exchange between two abled parties is the most crucial in the implementation of this software.

Another challenge to overcome for the uptake of the digital berth alignment tool is the larger environment. The maritime industry is known to be traditional and rather reluctant to open data exchange and transparent information sharing. This general perception needs to be overcome. Rolling out software solutions globally to an increasing number of terminals establishes this new process in the industry quickly. Standards provide the first cornerstone, as they supply the means to exchange data points in a structural and streamlined manner.

Lastly, the technology itself must grow and develop with the process and the adoption. Keeping the software up to date and easy to use will maintain the user experience and thus the application. Continuous tracking of usage across all stakeholders guarantees longevity. KPIs can support the efforts.

Overall, the findings indicate that considerable progress has been achieved in establishing digital berth alignment practices across participating organizations. However, the challenges lay with the partners and the traditional environment: Challenging the status quo in shipping requires visible efforts, convincing benefits, confidence in the approach, and persistence.

5.2 Limitations and Additional/Further Research

As this part of the larger research project was established very early on in the roll-out phase of the software, adaptation success was still very limited: Separation of age groups, gender, educational background, professional work experience in the field should be investigated and introduced to a future research setup. However, this early investigation throughout the ongoing change process was crucial and granted continuous improvement actions to increase uptake along the way.

Certainly, additional research on the quantitative side was done simultaneously and will be shared in the future: Two statistical analyses were exercised, which produced conclusions from the complete data set: A descriptive analysis and a relationship inferential statistic. The latter highlights progressions or correlations between two or more variables and emphasizes ‘statistically significant’ differences (O'Gorman and MacIntosh, 2015; Saunders et al., 2019).

Meanwhile, the change management question in digital adoption seems to be the main hurdle to overcome when digitalization is the aim. A simultaneous global roll-out along employees with various cultural backgrounds is rare, and proved to be a challenging research case. It shall be seen how the adoption process continues. Further research should investigate more locations, the intersections between the main driver of the software and the surrounding partners, and the reduction of waste (time loss, fuel, waiting times etc.).

Most interesting will be the just-in-time digital global optimization of the whole shipping network using artificial intelligence, bringing together vessels and quay in the most efficient way. Standards and digital solutions are paving the way: The findings suggest that standardized data exchange and interoperable digital solutions constitute essential prerequisites for the future digital transformation of container liner shipping.

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Benchmarking Winter and Polar Shipping Competencies: Finland-the United States-Australia Comparison

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Abstract: This study examines winter and polar shipping competencies in Finland, the United States, and Australia through a cross-regional benchmarking approach focused on operations, infrastructure, regulations, maritime education, competency frameworks, operational practices, and existing challenges. A mixed-method analysis was conducted using scientific literature, institutional reports, regulatory documents, and expert perspectives. Results show that Finland has developed a mature winter navigation and icebreaking system based on extensive Baltic Sea experience, advanced ice-class fleets, and strong public–private cooperation. The United States contributes expertise in Arctic and Antarctic operations, emphasizing regulatory oversight, risk-based navigation, and maritime academy training, although challenges remain due to aging infrastructure and limited Arctic capacity. Australia demonstrates strong capabilities in Antarctic logistics and environmental stewardship, supported by specialized Polar Code training and centralized government coordination. Across all regions, competencies extend beyond technical winter/polar navigation skills to include leadership, environmental awareness, digital systems, and operational decision-making in remote and uncertain environments. The study identified common challenges, including climate change, operational uncertainty, infrastructure limitations, and gaps between formal STCW requirements and practical operational needs. The findings highlight the complementary strengths of the three countries and the importance of international cooperation in developing future polar maritime competencies.

Keywords: competency benchmarking, environmental protection; winter navigation; Polar Code; STCW

1. Introduction

Interest in polar shipping continues to grow across both Arctic and Antarctic waters, driven by receding ice and the emergence of new navigable routes popularly known as shipping corridors in the Arctic this century (Lynch et al., 2022). Operating in these regions requires specialized competencies that go well beyond those used in conventional maritime navigation and voyage execution. IMO's goal-based standards, such as the Polar Code and the STCW framework (Table A-V/4-2), outline the foundational requirements for these competencies (International Maritime Organization, 2015; 2016). Actual implementation practices may differ significantly across regions and organizations.

This cross-regional study examines polar shipping competencies at maritime universities in Finland, the United States, and Australia. The study consisted of benchmarking the national context and operations, fleet and infrastructure, regulatory framework, maritime education and training, competency framework, operational practices, challenges and gaps. Environmental and nature-related competencies were also studied as an integrated dimension of responsible polar operations.

In this study, Finland is treated as a mature winter-navigation competence model rather than as a direct equivalent of Polar Code operations, recognizing that Baltic winter navigation develops many of the same skills required for polar navigation while operating under different regulatory conditions.

2. Methods

A mixed-methods benchmarking approach was used to compare winter and polar shipping competencies across Finland, the United States, and Australia. Benchmarking is understood as a structured comparison across predefined dimensions rather than quantitative performance measurement. The analysis combined three components.

1) Documentary review. Scientific literature, institutional reports, national strategies, and international regulatory documents (e.g., Polar Code, STCW amendments) were systematically reviewed. Documents were selected based on relevance to winter or polar operations, publication within the last 5–10 years, and explicit connection to maritime education and training, regulatory frameworks, or operational practices. 2) Expert perspectives. Expert input was obtained from 12 maritime professionals and educators, distributed as follows: Finland (4), United States (4), Australia (4). Experts included ice navigators, academy instructors, icebreaking authorities, and regulatory personnel. Experts were selected using purposive criteria: at least 10 years of relevant experience, direct involvement in winter or polar operations, and affiliation with maritime universities or competent authorities.

Data was collected through structured interviews and written questionnaires. Questions focused on: competency needs in winter/polar operations. training practices and simulator use, regulatory implementation challenges, operational decision-making in ice and environmental and digital competency requirements

Expert responses were analyzed using thematic coding, with codes aligned to the seven benchmarking dimensions and the four competency domains. Themes were cross-checked against documentary evidence to ensure triangulation.

3) Structured comparative analysis. Findings were organized into a benchmarking matrix covering seven dimensions: national context and operations, fleet and infrastructure, regulatory framework, maritime education and training, competency framework, operational practices, and challenges and gaps.

To ensure analytical consistency, competencies were grouped into four domains, *i.e.* technical, human, environmental, and digital, and applied equally to all three countries.

3. Results and discussion

3.1. National context and operations

Finland's maritime operations are primarily focused on the Baltic Sea, where seasonal ice conditions require continuous winter navigation. Although the Baltic Sea is not classified as a polar region, its ice conditions necessitate competencies similar to those required in Arctic operations. Winter navigation is essential for maintaining national logistics and economic stability. Finnish strategies emphasize security of supply, sustainable maritime transport, and international Arctic cooperation. The Arctic dimension is reflected in national policies, although operational activity remains concentrated in the Baltic region.

The United States operates in both the Arctic and Antarctic regions. Arctic activities are concentrated in Alaska and areas surrounding the Beaufort & Chukchi Seas, while Antarctic operations support research stations such as McMurdo, Palmer, and Scott Pole Station. The U.S. also plays a strategic and security role in the polar regions, supported by the U.S. Navy and Coast Guard.

Australia's polar operations are focused exclusively on Antarctica. Activities are driven by scientific research, logistics, and environmental stewardship. The Australian Antarctic Strategy outlines long-term priorities, including sovereignty, sustainability, and safe operations.

Across the three countries, these operational contexts illustrate fundamentally different drivers of competency development: Finland's winter navigation model emphasizes continuity and logistics resilience; the United States' dual Arctic-Antarctic presence requires regulatory oversight and strategic readiness; and Australia's Antarctic-focused system prioritizes scientific logistics and environmental stewardship. These distinctions shape nature and emphasize competencies required in each national setting.

3.2 Fleet and infrastructure

Finland maintains a highly developed winter navigation system, including icebreakers and ice-class commercial vessels. The Finnish–Swedish Ice Class Rules (FSICR) define vessel requirements, with most ships operating in high ice classes such as 1A and 1A Super (Traficom & Swedish Transport Agency, 2019). Icebreakers

play a central role in ensuring year-round navigation. These vessels are operated through a public-private model in which private companies provide services under government contracts.

The U.S. polar fleet includes icebreakers such as the Polar Star and Healy, as well as research vessels. However, the fleet is aging and limited in capacity. Infrastructure in the Arctic is minimalist and rudimentary, with few deep-water ports spread over distances between operational bases. Efforts are underway to expand the fleet under the ICE Pact, which aims to deliver new icebreakers in the coming years.

Australia operates a single specialized icebreaking research vessel, RSV Nuyina, which supports logistics, scientific missions, and aviation operations (Australian Antarctic Division, 2022). The vessel represents a significant investment in modern polar capability. Operations are centralized and coordinated through government agencies, with Hobart serving as the primary gateway.

In comparative terms, Finland maintains the most extensive and technically advanced icebreaking and ice class fleet, the United States faces capacity constraints due to an aging and limited polar fleet spread across two hemispheres, and Australia operates a single modern vessel optimized for Antarctic logistics. These differences highlight significant variation in national capability, redundancy, and operational resilience.

3.3. Regulatory framework

The Polar Code is implemented in Finland but is not applied to domestic Baltic operations. Maritime regulation is enforced by national authorities, including Traficom and the Finnish Border Guard. Environmental protection is primarily governed by international conventions, such as MARPOL.

The Polar Code is implemented through U.S. Coast Guard regulations (U.S. Coast Guard (USCG), 2022). Compliance is enforced through certification, inspections, and operational controls. Additional measures include vessel-specific requirements and environmental regulations such as the Vessel Incidental Discharge Act.

In Australia, the national strategy is primarily driven by the Australian Antarctic Division (a Commonwealth/national government agency) under the Australian Antarctic Strategy and 20 Year Action Plan (2016–2036), which emphasizes sovereignty, environmental stewardship, scientific research, and safe logistics (Australian Government, 2016). Australia implements the Polar Code through national legislation and regulations. Environmental protection is particularly stringent due to obligations under the Antarctic Treaty System (Australian Antarctic Division, 2023). Additional measures include biosecurity controls and environmental impact assessments.

Taken together, the three regulatory systems demonstrate varying scopes and enforcement cultures: Finland applies the Polar Code only to international voyages, while relying on national rules for Baltic operations; the United States enforces a comprehensive regulatory regime through the U.S. Coast Guard; and Australia integrates Polar Code compliance within a stringent Antarctic Treaty-based environmental governance system. These differences influence how competencies are defined, taught, and operationalized.

3.4. Maritime education and training

Maritime education in Finland is based on STCW requirements. Polar training is available in vocational maritime schools and universities of applied sciences, such as SAMK, but is not mandatory unless seafarers operate in polar regions. As a result, formal training in winter navigation remains limited despite its operational importance.

In the USA, polar training is provided by institutions such as Maine Maritime Academy and Massachusetts Maritime Academy. Training includes basic and advanced courses aligned with STCW requirements. However, training is mandatory only for specific roles and operations, making it conditional rather than universal.

The Australian Maritime College provides basic and advanced Polar Code training aligned with STCW requirements (International Maritime Organization, 2016). Training includes simulator-based polar navigation and vessel-maneuvering exercises, case-study analyses, and desktop exercises on human factors. Training is mandatory for personnel operating in polar waters. (AMC Search, n.d-a.).

Comparatively, Finland's MET system emphasizes winter navigation without mandatory polar training, the United States provides STCW-aligned polar courses on a conditional basis, and Australia mandates structured Polar Code training for Antarctic operations. As a result, the level of formalized polar-specific competency development varies substantially across the three countries.

3.5. Competency framework

To ensure analytical consistency, the findings across Finland, the United States, and Australia were interpreted using a four-domain competency matrix covering technical, human, environmental, and digital competencies. This matrix provides a common structure for comparing how each country develops and applies competencies relevant to polar and cold region operations, addressing the unevenness noted in previous comparative studies.

Finland demonstrates strong technical competencies in winter navigation and ship design. Human and organizational competencies are well developed through coordination between public authorities and private operators. Environmental awareness is high due to the Baltic Sea's sensitivity. Digital competencies are evolving, with increasing use of ice data and navigation systems.

Technical competencies in the USA are defined by STCW, with emphasis on polar navigation and vessel performance (US Department of Homeland Security, 2018; U.S. Coast Guard (USCG), 2024). Human competencies focus on decision-making and leadership in uncertain conditions. Environmental competencies are reinforced through strict regulatory frameworks. Digital competencies include the use of satellite data and simulation tools.

Australia emphasizes technical competencies in polar navigation and vessel handling. Human competencies focus on decision-making in isolated environments, with a strong emphasis on crew and passenger safety. Environmental competencies are strongly integrated into operations. Digital competencies include advanced simulation and satellite-based systems.

When viewed through the four-domain competency matrix, Finland demonstrates particular strengths in technical winter navigation and ship design; the United States emphasizes regulatory, leadership, and risk-based competencies; and Australia integrates environmental and human factors competencies most strongly. These patterns reflect the operational demands and regulatory environments of each country.

3.6 Operational practices

Finland represents a mature winter navigation and icebreaking assistance system, supported by long-standing operational experience, coordinated traffic management, and ongoing competency development initiatives such as the WINMOS III project (WINMOS III n.d.-a.).

In the USA, operations are conducted using a risk-based approach guided by the Polar Code. Icebreaker support, satellite data, and adaptive voyage planning are critical components. Decision-making is influenced by real-time environmental conditions. Environmental compliance remains a defining feature of US polar operations. Ongoing regulatory initiatives include stricter fuel standards and the potential expansion of Emission Control Areas (ECA). It reflects a broader commitment to addressing the environmental footprint of Arctic shipping (EPA, 2020; PAME, 2023).

Australian operations are conducted as centralized logistics missions rather than commercial shipping routes. Decision-making is precautionary and heavily reliant on environmental data. There is no permanent icebreaker escort system, and traffic management is limited.

Operationally, Finland’s coordinated winter navigation system contrasts with the United States’ risk-based polar operations and Australia’s centralized Antarctic logistics model. These differences underscore how operational environments shape national approaches to voyage planning, decision-making, and environmental protection.

3.7. Challenges and gaps

In Finland, a key challenge is the mismatch between formal training requirements and operational realities. Winter navigation is not fully addressed in standard STCW training, creating a competency gap. Climate change is increasing ice variability, adding uncertainty to navigation.

The United States faces significant challenges, including an aging fleet, limited infrastructure, and long response distances in the Arctic. Communication systems and hydrographic data are also limited. Climate change is increasing environmental risks and operational uncertainty. Legally, the US has not ratified MARPOL Annex IV, creating a persistent gap in sewage-discharge governance in Polar waters (IMO 1973/78). In terms of scope, the Polar Code does not apply to fishing vessels or ships with a gross tonnage of less than 500 GT, leaving a substantial portion of the Arctic shipping fleet outside mandatory safety and environmental requirements (IMO 2015).

Australia has no redundancy in its single-vessel icebreaking capability; unscheduled maintenance during the 2021/22 and 2022/23 seasons necessitated chartering alternative vessels (Australian Antarctic Division, n.d.). Other challenges include high operational costs and extreme remoteness. Climate change is altering ice conditions, increasing uncertainty and operational risks. Australian missions already face severe weather conditions at 50°S, and the future impacts of climate change in the Southern Ocean are challenging to predict (Cai et al., 2023).

Overall, the three countries face different but complementary challenges: Finland's training-requirement mismatch, the United States' infrastructure and fleet limitations, and Australia's single-vessel dependency and extreme remoteness. These structural constraints influence how competencies are prioritized and developed within each national MET system.

4. Conclusions

This study benchmarked maritime competencies in the winter and polar regions across Finland, the United States, and Australia using a structured mixed-methods approach. By applying a common analytical framework across seven dimensions and a four-domain competency matrix, the study provides a clearer basis for comparing how different national MET systems develop and operationalize competencies relevant to high latitude operations.

The findings (Table 1) show that each country's operational environment shapes its competency strengths: Finland's mature winter navigation and icebreaking system supports strong technical and organizational competencies; the United States emphasizes regulatory oversight, leadership, and risk-based decision-making across Arctic and Antarctic operations; and Australia integrates environmental governance and human factor competencies through its Antarctic logistics model. These differences highlight the diversity of pathways through which polar-relevant competencies are cultivated.

The comparative framework (Table 2) and Table 1 offer a practical tool for MET institutions seeking to map existing curricula, identify gaps, and explore areas for cooperation. The tables can be used to align course content with operational realities, support joint training initiatives, and guide future research on competency development in polar and cold region contexts.

Table 1. Dimensions of winter navigation in Finland and polar operations of the United States and Australia.

Dimension	Finland	The United States	Australia
Operational Focus	Baltic winter navigation	Arctic + Antarctic	Scientific research, Antarctic logistics
Fleet	Strong icebreaker system	Aging, expanding	A single advanced vessel
Training	STCW-based, limited polar focus	Conditional training	Structured Polar Code training
Strength	Winter navigation expertise	Regulatory framework	Environmental governance
Gap	Training mismatch	Infrastructure & fleet	Limited redundancy

Table 2. The four-domain competency matrix applied to Finland, the United States and Australia.

Competency Domain	Finland	The United States	Australia
Technical	Advanced winter navigation; strong ice-class ship design; coordinated icebreaking system	STCW-aligned polar navigation; vessel performance in ice; risk-based voyage planning	Polar navigation and vessel handling; aviation-at-sea integration; ice-edge operations

Human	Strong coordination between authorities and private operators; crew resource management in winter conditions	Leadership in uncertainty; decision-making in remote Arctic/Antarctic settings	Safety-critical decision-making in isolated environments; passenger and scientific personnel management
Environmental	High environmental awareness due to Baltic sensitivity; MARPOL-aligned practices	Strict environmental compliance; ECA-related measures; sewage-discharge governance gaps	Strong Antarctic Treaty-based environmental stewardship; biosecurity and impact assessments
Digital	Increasing use of satellite ice data; evolving digital navigation tools	Satellite data, simulation tools, and digital voyage planning systems	Advanced simulation, satellite-based systems, and integrated logistics-environmental monitoring

The comparative analysis (Table 2) shows that some competencies and training practices are transferable across national contexts, while others are inherently context-specific.

Transferable elements include:

- simulator-based training for ice navigation and risk-based decision-making
- integration of environmental and human-factor competencies into MET curricula
- digital tools such as satellite ice data, decision-support systems, and advanced simulation
- structured competency frameworks that align technical, human, environmental, and digital domains

These elements can be adopted by MET institutions regardless of operational environment.

Context-specific elements include:

- Finland's icebreaking infrastructure and continuous winter-navigation system
- the United States' dual-hemisphere regulatory and strategic posture
- Australia's centralized Antarctic logistics model and Treaty-driven environmental governance

These reflect national operational realities and cannot be directly replicated, but they offer valuable insights for curriculum design and scenario-based training.

The four-domain competency matrix and the expanded comparative tables provide a practical tool for MET institutions seeking to map curricula, identify gaps, and design joint training initiatives. The benchmarking framework is preliminary, but it offers a transferable methodology for future cooperation in polar shipping education, training, and research.

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VR-Constructed Scenario Mapping: A Method for Supporting Design Translation in Complex Maritime Systems

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Abstract: This paper addresses a key challenge in human-centred ship bridge design: designers, who are usually non-domain experts, have difficulties understanding the context of use in complex socio-technical systems, thus are limited in their ability to generate contextually grounded design solutions. As a methodological intervention, this paper proposes VR-constructed scenario mapping, an immersive extension of layered scenario mapping to enable first-person, role-based exploration of operational scenarios. A controlled experiment framework is used to operationalise and examine a transformation chain linking scenario comprehension and design translation through VR-based and text/image-based scenario representations. Measures include cognitive load (NASA-TLX), scenario comprehension scores, and structured design outputs (spatial layouts and interface annotations). The study contributes a methodological framework for implementing and assessing the translation from contextual understanding to external design representation. By positioning immersive environments as epistemic tools rather than visualisation media, the study demonstrates the feasibility of observing and assessing design translation within a structured methodological framework for complex maritime systems.

Keywords: VR-constructed scenario mapping; ship bridge; maritime interfaces; design translation; human-centred design

1. Introduction

Digitalisation has transformed maritime operations into the highly complex socio-technical systems, where decision-making relies on the interaction of human operators, distributed information systems, and organisational procedures. Today's ship bridges are no longer defined by physical controls and visual navigation. Instead, they are characterised by multiple layers of digital information, automated systems, and collaborative workflows (Hollnagel, 2017; Stanton *et al.*, 2017). Such developments improve efficiency and safety. However, they also introduce significant cognitive complexity, particularly in situations that require rapid interpretation and coordination under conditions of uncertainty. To design effectively in such a modern digitalised system, the context of use of the ship bridge must be understood including operational constraints, spatial configurations, and team coordination. Human-Centred Design (HCD), formalised in ISO 9241-210, stresses the importance of basing design decisions on a deep understanding of users, tasks, and environments (ISO, 2019). In the maritime domain, Human-Centred Maritime Service Design (HCMSD) has emerged as an approach that incorporates HCD principles into maritime service systems and apply them to complex, safety-critical systems by demanding participatory and context-driven methods (Lützhöft and Dekker, 2002). Despite these frameworks, recent evidence indicates that maritime safety risks persist due to lack of grounding interface designs in the context (Hsieh, Xia and Chen, 2024).

A main challenge is that designers, especially those lacking domain expertise, often struggle with internalising fragmented operational knowledge and translating it into actionable design decisions, even though they have access to large amounts of information. Field studies, documentations, and expert interviews can be rich sources of data, but such information is often scattered across different formats, disciplines, and levels of abstraction. As a result, designers may fail to construct coherent mental models of the whole system, which limits their ability to detect latent problems and identify pain points in real-world operational settings. This challenge can be understood as an internalisation-translation gap, that refers to the difficulty designers have in transforming fragmented knowledge into actionable design representations. The processes of internalisation and externalisation have been discussed in knowledge management (Nonaka and Takeuchi, 1995) but this gap has

not been explicitly addressed in the context of design cognition. Existing HCD methods provide limited support to bridge this gap. Text-based materials and static visualisations often incapable to representing the dynamic and spatially situated features of socio-technical systems (Vicente, 1999). Even participatory approaches are limited due to high costs, low accessibility, and the difficulty of simulating rare or emergency situations.

Recent developments in Virtual Reality (VR) provide new opportunities to address this challenge. Immersive environments allow users to experience complex systems from a first-person perspective to support situated perception and interaction (Slater and Sanchez-Vives, 2016). VR immerses users in scenarios that are structured spatially and temporally, which results in a more embodied and integrated understanding of the system dynamics. Previous research has demonstrated VR's potential in training, simulation, and spatial cognition tasks (Radianti *et al.*, 2020). Recent studies further highlight extended reality (XR) as a promising tool to reduce cognitive overload and enhance situational awareness by overlaying digital information on top of elements in real-world navigation (Nordby *et al.*, 2024). However, the role of immersive media in supporting early-stage design cognition, i.e. the transformation from the internal understanding to external design solutions, is underexplored.

To fill this gap, we propose in this paper the VR-constructed scenario mapping, a method that enables designers to engage with complex operational scenarios through immersive, role-based exploration. This approach builds understandings of complex maritime contexts by guiding participants to experience time-sequenced scenarios with embedded multiple information layers that reflect real-world operational dynamics. Importantly, the method links this experiential understanding to the tasks of design translation, where the participants externalise their internalised knowledge into spatial layouts and interfaces.

In this paper, we build upon our previous work by incorporating the VR-based scenario construction into a systematic methodological framework and linking it to measurable design outcomes. Rather than evaluating the effectiveness of specific design solutions, we conceptualise design as a transformation process: from scenario exposure, through comprehension and mental model formation, to externalised design representations. By operating this process within a controlled experimental framework, this study demonstrates how the proposed transformation chain can be operationalised, observed, and assessed.

2. Theoretical Framework

To understand how designers engage with complex operational systems, we need to integrate insights from fields of socio-technical systems theory, human-centred design, embodied cognition, and design research. This paper presents a theoretical framework which conceptualises design as a transformation process of multi stages connecting perception, cognition, and externalisation.

2.1 Complexity in Socio-Technical Systems

Maritime operations are complex socio-technical systems, whose performance is dependent on the interactions between human operators, technical equipment, and organisational structures (Hollnagel, 2017). Such systems cannot be simplified to individual components, but are characterised by distributed cognition in which information processing is distributed across people, tools, and environments (Hutchins, 1995).

Navigational decisions on a ship bridge are made by integrating information from multiple sources (e.g., radar, ECDIS, visual observation, etc.) and between roles such as Master, Officer of the Watch (OOW), and Helmsman. These interactions take place in constrained physical spaces and under dynamic conditions that require continual adaptation. As Vicente (1999) argues, the design of such systems must be effective not only for interface usability but also for the underlying constraints that shape human action. However, these constraints are often opaque for non-domain designers. Without first-person experience of domain exposure, it is difficult to perceive the interplay among spatial layout, information distribution, and communication structures.

2.2 Human-Centred Design and Context of Use

Human-Centred Design emphasises the need to understand the context of use as determined by the users, tasks, equipment, and environments in which a system is being used (ISO, 2019). In theory, this principle ensures that design decisions are consistent with conditions in the real-world. However, in practice it is difficult to achieve such understanding especially for specialised domains. Such methods like field observation,

interviews, and scenario-based design are designed to capture contextual information(Carroll, 2000). However, the methods often produce fragmented representations that require interpretation and synthesis. Designers have to construct coherent mental models out of these fragmented information resources.

In maritime design, this situation is amplified by the nature of safety-critical and the rarity of such scenarios as emergencies, which are difficult to observe directly. Consequently, designers may have to rely on simplified or incomplete representations of system behaviour to identify potential problems and design opportunities. This limits their design thinking and invalidates design solutions in real use scenarios.

2.3 Embodied Cognition and Immersive Understanding

Embodied cognition provides a theoretical foundation for how immersive environments can facilitate learning and understanding. From this perspective, cognition is not limited to abstract reasoning, but is rooted in perception and action within the environment (Wilson, 2002). Physical experience and movement are more connected to spatial understanding.

The Virtual Reality makes it possible for users to interact with environments in a first-person, sensorimotor way, which helps to create the illusion of presence which Slater and Sanchez-Vives (2016) described. This sense of "being there" provides users with more direct perception of spatial relationships, constraints, and affordances than they receive through symbolic representations. Studies have shown that immersive environments can enhance spatial cognition and situational understanding, especially in navigational tasks and complex environments (Radianti *et al.*, 2020). In terms of design, it suggests that VR may support the internalisation of context by enabling designers to experience system dynamics.

2.4 From Scenario Comprehension to Design Translation

Immersive experiences may contribute to understanding, but the question is how to translate that understanding into design. The role of external representations such as sketches, diagrams and prototypes has been emphasised for a long time in design research to make ideas explicit and communicable (Schön, 2017; Cross, 2025). However, the link between internal understanding and external representations is still under-explored empirically.

In this paper, we use the term design translation to describe this process, which refers to the transformation of internalised mental models of a system into an explicit design solution. It involves selecting relevant information, prioritising constraints, and mapping these onto spatial or interface configurations. This is a critical process for mental models, just as s Norman (1983) claims that both users and designers develop internal representations of the systems they use that influence their actions and expectations. When the mental models are incomplete or inaccurate, design decisions may fail to address critical constraints. Instead, the more comprehensive mental models are developed, the more context-sensitive design solutions would be produced. To capture this process empirically, we conceptualise design as a transformation chain shown in the Figure 1. In this framework, scenario exposure refers to allowing designers to experience the operational scenario simulated from real ones; scenario comprehension refers to extracting of any task-relevant elements from a dynamic scenario and mapping them to the physical, cognitive, and organizational dimensions of human factors; mental model formation is the internalising process to construct obtained information; while design translation is the externalisation of this understanding into the design outputs.

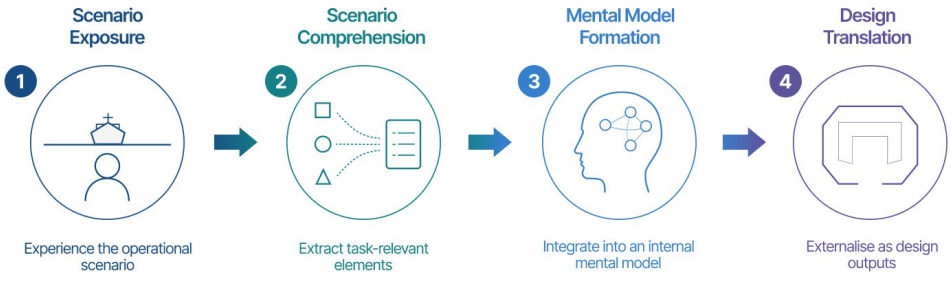


Figure 1. The transformation chain of design

For these purposes, VR-constructed scenario mapping is proposed that supports and observes this transformation. The method provides an practical and measurable approach to study the role of immersive

understanding in design, by deconstructing scenario experiences into multiple information layers (*scenario description, decision-making, tasks and goals, operations and activities, equipment utilization, involved actors and their positions, required information, and VR-provided touchpoints*) and dynamically assembling in VR(Mu, Bin Guo and Chu, 2024), and then connecting them with measurable design outcomes.

3. Method Overview

3.1 From Layered Scenario Mapping to VR Implementation

The proposed method is based on the concept of layered scenario mapping, which was originally introduced by Lurås (2016). Layered scenario mapping structures complex operational situations into multiple interrelated layers, enabling designers to represent not only physical configurations but also decision-making processes, actor roles, and system interactions. This makes implicit relationships explicit and thus results in a more holistic understanding of socio-technical systems. However, the traditional layered scenario mapping is implemented in the form of static & paper-print representations (e.g., diagrams, images, textual descriptions), which still require designers to cognitively reconstruct dynamic interactions and spatial constraints. This limitation is particularly evident for non-domain designers who may not have the experience base to integrate them into a coherent mental model.

To overcome this limitation, this study extends layered scenario mapping into an immersive format via VR-constructed scenario mapping, which was introduced in our previous work to demonstrate the potential of virtual reality as a support tool for human-centred ship bridge design (Mu, Bin Guo and Chu, 2024). Meanwhile, this approach in the present study is extent from a representation tool to a structured methodological framework. In particular, it formalises the decomposition, reconstruction and experience of scenario information, and how the experience can be systematically related to measurable design outcomes. Rather than a medium of visualisation, VR is regarded as a cognitive mediation to facilitate the transformation from fragmented knowledge into actionable design representations.

3.2 VR-Constructed Scenario Mapping

VR-constructed scenario mapping transforms layered scenario representations into an interactive, first-person, and role-based experience. The method decomposes operational scenarios into multiple information layers and then reconstructs and synchronises them in a virtual environment, so that participants to experience how they interact over time and space. Participants engage with an integrated socio-technical system instead of interpreting isolated pieces of information. This transformation is consistent with principles of embodied cognition, in which understanding arises from perception-action coupling in an environment (Wilson, 2002). The method aims to help participants to internalise the complex system's constraints and relationship by situating them in the operational context.

The method conceptualises design as a transformation process as illustrated in Figure 1 above. The framework draws on theories of situation awareness (Endsley, 1995), distributed cognition theory (Hutchins, 1995), and design cognition theory (Cross, 2025). The scenario exposure provides structured experiential input and the scenario comprehension captures participants' ability to extract task-relevant understandings. Then the understandings are mediated through mental models (Norman, 1983), and externalised into tangible design solutions by design translation.

4. Experimental Design and Measures (Integrated in the Transformation Chain)

4.1 Experimental Design and Participants

This study employs a between-subjects experimental design to examine how different representations of scenario (VR vs. Text/image based) facilitate the transformation from scenario exposure to design translation. Participants were 24 design students (industrial design and interaction design) without maritime experience, selected to reflect non-domain designers who interact with complex systems through indirect representations. They were randomly assigned to either a VR-based immersive condition or a text/image-based condition with scripted guidance. Prior research indicates that representation forms significantly influence mental model development. (Norman, 1983; Carroll and Olson, 1988; Payne, 2007). To clarify, although the sample size is modest, it is consistent with exploratory and methodology-oriented studies in design cognition and immersive

environments, where the primary objective is to evaluate the feasibility of an experimental framework rather than to establish population-level effects. Furthermore, the experimental session lasted over 45 minutes for each participant, limiting the practical scale of data collection.

4.2 Scenario Exposure and Controlled Representation

The experimental design created a real contextual experience for the scenario exposure phase while maintaining information equivalence between the two exposure conditions. Participants were exposed to a time-sequenced maritime navigation scenario extracted from CCTV recordings of a real training session in the ship bridge simulator. The informative content and exposure time of both experimental conditions (VR-based and text/image-based) were strictly standardised: 2.5 minutes were dedicated to each scenario sequence. The training scenario comprised four distinct event sequences, representing the following operational states:

- Baseline Navigation: The vessel engages in a routine approach to the port.
- Increased Task Load: The bridge team is alerted by a Very High Frequency (VHF) radio call from Port Control. The port is closed and vessel traffic is temporarily suspended due to sustained winds of 55-knot. As a result, the bridge team immediately decides to change course northward toward sheltered waters while awaiting further instructions.
- Collaborative Complexity: Sea fog rises, restricted visibility to 1 nautical mile. Consequently, the bridge team must act strictly in accordance with COLREGs Rule 19 (Conduct of vessels in restricted visibility).
- Emergency Failure: Failure of the vessel's autopilot. The helmsman must take over the manual steering duties, while others continue to navigate through the environmental hazards of winds and fog.

To evaluate these scenarios, participants were assigned to one of two exposure conditions:

- VR Exposure Condition: The physical ship bridge simulator recorded in the original training footage was modelled at a 1:1 scale in the VR environment (see Figure 2). To meet the agile development, the 3D model was not high-fidelity rendered, yet all essential bridge equipment, instrumentation, and user interfaces were properly maintained. Within this environment, participants experienced the scenario from a first-person perspective with structured role switching (a Master, two OOWs, and a Helmsman). The other actors were represented as simplified non-player characters (NPCs) to maintain participants' awareness of the team structure.
- Text/Image-based Condition: Participants in this condition were provided with comprehensive 2D reference materials, such as photographs of the physical simulator and a detailed spatial floor plan. To ensure the same narrative structure and time segmentation as the VR condition, the layered scenario information map (a 2D illustration) was also presented in couple with scripted, stage-by-stage materials accompanied by specific role prompts.



Figure 2. The 1:1 scale modelled ship bridge in VR

4.3 Scenario Comprehension and Cognitive Processing

After each scenario state, participants were asked to complete a brief scenario comprehension test, which is a single-choice question designed to constrain situational understanding rather than recall the memory of the experiential scenario. These questions were designed to probe participants' ability to understand spatial

constraints, coordination dependencies, and information flow in operational environments. The approach is conceptually informed by situation awareness research (Endsley, 1995), in particular the emphasis on comprehension of system relationships (Level 2 Situational Awareness), but it is intentionally simplified to suit non-expert participants and short experimental duration. Unlike full SAGAT implementations, no freeze-probe technique was used, instead, comprehension was assessed immediately after each state to minimise disruption to scenario continuity. The total comprehension score (e.g. if the participant answers all four questions correctly, the total score will be 4 points) serves as a constrained behavioural indicator of how effectively participants internalised the scenario structure.

4.4 Design Translation Tasks

The next stage of the experiment, participants externalised their understanding through two design tasks, representing the transition between mental model and design translation.

First, a spatial layout task required participants to reconstruct a ship bridge configuration by placing predefined elements (e.g., equipment, console tables, crew members) onto an answer sheet of the ship bridge's blank floor plan. Layout outcomes were assessed based on operational constraints, such as visibility and communication continuity between key roles, safe interpersonal spacing, and clustering of functionally related equipment, rather than aesthetic quality. These criteria are derived from ship bridge design principles and reflect the spatial dimension of distributed cognition, where cognition is shaped by the arrangement of artefacts and actors in space (Hutchins, 1995).

Second, an interface annotation task required participants to identify critical and redundant information on Radar and ECDIS interface screenshots captured from existing products. Using a limited number of tokens to highlight or suppress specific information presented. This task captured participants' ability to prioritise information at the cognitive level. The evaluation is derived from established principles of attention and information priority in complex systems (Wickens *et al.*, 2021), to examine whether participants' annotations align with relevant information regions or specific collision avoidance indicators in maritime interfaces.

To improve scoring transparency and operational validity, both tasks' assessment criteria were refined in consultation with a practicing third mate and a maritime human factor professional. Layout outcomes were aggregated into a total score using a binary scale against the predefined rubric, while annotation outputs were scored according to the relevance to collision avoidance, navigational awareness, and task prioritisation requirements.

4.5 Supporting Measures and Behavioural Evidence

In addition, participants completed a pain-point elicitation task by identifying 3-5 perceived issues. These responses were coded into three human factor levels (physical, cognitive, and organizational) corresponding to increasing depth of system understanding, where the distribution of higher-level (cognitive and organisational) insights served as an indirect indicator of design empathy and depth of internalisation.

Subjective workload was assessed with the NASA-TLX (Hart and Staveland, 1988) to evaluate the cognitive processing stage of the transformation chain. To account for the individual differences, a spatial ability test (paper folding test) and a perceived media interference questionnaire were included as covariates for subsequent analysis.

In the VR condition, behavioural telemetry (e.g., head position, rotation, proxy gaze) were collected to provide supplementary evidence to interpret the participants' attention allocation. Consistent with prior VR-based human factors studies (Radianti *et al.*, 2020), these telemetry patterns help to explain performance by offering process-level insights.

Overall, the experimental design integrates multiple measures aligned with the transformation chain: cognitive load reflects the processing cost of participants, the scenario comprehension test captures intermediate understanding, and design tasks enable the externalisation of mental models.

5. Methodological Contribution

This methodological proposes and operationalises VR-constructed scenario mapping as an empirically testable method for human-centred design of complex socio-technical systems.

Firstly, it transforms layered scenario mapping (Lurås, 2016) from a static representational method into an immersive and experiential format, enabling designers to directly perceive the spatial, temporal, and organisational-relationship-involved context rather than inferring them from fragmented materials.

Secondly, it introduces a transformation-chain-based evaluation framework that explicitly links scenario exposure, cognitive processing, and design translation. This framework addresses a challenge in both design research and maritime human factors, which is the relationship between contextual understanding and design output is often assumed but rarely measured.

Thirdly, it proposes a multi-level measurement strategy combining subjective workload (NASA-TLX), scenario comprehension, structured design outputs, and behavioural telemetry. Instead of abstract descriptions of the design outputs' strengths and weaknesses, design translation can be represented and interpreted through a set of metrics.

Finally, the method bridges design cognition and maritime operational context, demonstrating its potentials in establishing reusable scenario-based knowledge for future design applications.

6. Conclusion and Future Work

This study presents VR-constructed scenario mapping as a structured approach for observing and evaluating design translation within complex socio-technical contexts. By integrating layered scenario mapping technique with VR, this method shifts the immersive technology from a visualisation medium to an epistemic tool in design processes. It enables non-domain designers to experience operational scenarios systematically and externalise their understanding into measurable design outputs.

However, as an exploratory methodological investigation, there are several limitations. Primarily, the participant sample was relatively small and therefore precludes strong statistical claims regarding generalisability. Consequently, the findings should be interpreted as preliminary evidence supporting methodological feasibility rather than definitive proof of overall effectiveness. Additionally, this study concentrates on non-domain designers and controlled scenarios, which doesn't fully capture the complexity of real operations.

Large-scale empirical validation remains a necessary direction for future research to evaluate the robustness, generalisability, and potential effectiveness of the proposed framework. Furthermore, future studies should involve a broader panel of maritime professionals and domain experts from multi-disciplines to rigorously assess the operational validity of the generated design outcomes. As the maritime industry transitions towards Maritime Autonomous Surface Ships (MASS) and remote-control centres, the challenge for designers to internalise distributed operational contexts is likely to amplified (Gernez *et al.*, 2024). Future iterations of the methodology may support the design of these next-generation remote interfaces through the establishment of immersive, scenario-based knowledge repositories.

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Comparative Analysis of Motor Current and Stray Flux Signature Methods for Induction Motor Faults Detection in Maritime Systems

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Abstract: Fault detection of induction motors on ships at early stages is very important to ensure the reliability, high performance, and safety of ship operations and navigation. Among different non-invasive fault detection techniques, Motor Current Signature Analysis (MCSA) is a well-established method. In this paper another non-invasive method, Stray Flux Signature Analysis (SFSA) is considered due to its effectiveness and applicability. A comparative analysis of two fault detection techniques is presented based on experimental analysis carried out on an induction motor operating under healthy and faulty conditions in steady state. The experiments are conducted on a squirrel cage induction motor with three different types of faults: broken rotor bar (BRB), bearing fault (BF) and combination of BRB and BF. In this proposed work, SFSA is used by placing a search coil on the motor frame to detect stray flux signals. The MCSA will also be implemented with the use of a current probe to detect the current signals. The signals obtained from both methods will be processed and analyzed, using Fast Fourier Transform (FFT), to extract characteristic harmonics which are attributed to different types of faults. The outcome of this research is expected to provide a better understanding of the application and limitations of SFSA and MCSA in the diagnosis of combined fault.

Keywords: induction motor, stray flux signature analysis, motor current signature analysis, combined faults

1. Introduction

Induction motors have become vital components of marine and industrial facilities owing to their durability, efficiency, and simplicity. Nevertheless, they can suffer from different types of faults, some of which might cause system failure. In this context, it is important to utilize proper fault detection techniques. There are many existing techniques of motor fault diagnosis, however, Motor Current Signature Analysis (MCSA) has been applied most frequently since it provides the possibility of conducting non-invasive tests. At the same time, this method may be less efficient in situations where multiple faults are present in the system. Recently, Stray Flux Signature Analysis (SFSA) has attracted increasing interest among researchers since it allows capturing stray magnetic flux that contain information about electromagnetic and mechanical faults. Earlier studies conducted by the authors have emphasized that there is a lack of research regarding the application of SFSA to diagnose multiple faults such as broken rotor bars and bearings (Čulić *et al.*, 2025). This work provides an analysis of the condition monitoring methods in induction motors, particularly in maritime applications and extends the findings in (Čulić *et al.*, 2025) by providing comparison of MCSA and SFSA under combined fault condition. An experiment was conducted using a squirrel cage induction motor under three conditions: normal condition and three fault conditions, broken rotor bar (BRB), bearing fault (BF) and combination of these two faults.

2. Faults under study

This chapter examines the identification and analysis of faults in electrical machines, emphasizing their causes and effects on system performance. It particularly addresses bearing faults and broken rotor bar faults, as these are among the most common issues affecting reliability and efficiency.

2.1 Bearing fault

Bearing faults are among the most common types of failure in induction motors. These failures account for approximately 41% of all recorded faults in induction motors (Gangsar and Tiwari, 2020). In terms of functionality, bearings facilitate motor operation by providing support for the shaft, aligning it properly, and minimizing friction by using lubricants. In terms of structure, bearings contain an outer ring, an inner ring, and rolling elements between, as shown in Figure 1.

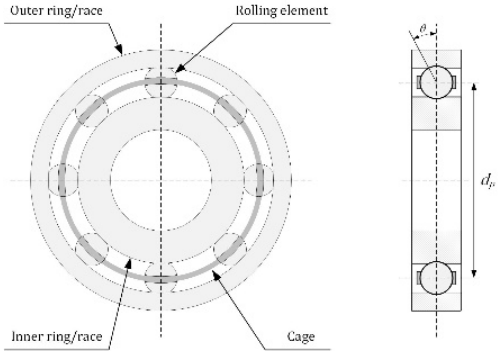


Figure 1. Bearing construction elements and cross section view; (Source: Authors).

In case of bearing faults, they often produce periodic impact waves, known as shock pulses. The frequencies of shock pulses vary depending on a number of variables, including the geometry of the bearing, the rotation speed, and the component where the defect occurs (Ruiz-Sarrio, Antonino-Daviu and Martis, 2024). When considering the best scenario when the outer race is fixed while the inner race is rotating, typical fault frequencies may be derived from the formulas (Čulić *et al.*, 2025):

$$f_{BPO} = \frac{n_b}{2}\left[1 - \frac{d_b\, cos(\theta)}{d_p}\right] f_r \tag{1}$$

$$f_{BPI} = \frac{n_b}{2}\left[1 + \frac{d_b\, cos(\theta)}{d_p}\right] f_r \tag{2}$$

$$f_C = \frac{1}{2}\left[1 - \frac{d_b\, cos(\theta)}{d_p}\right] f_r \tag{3}$$

$$f_{BS} = \frac{d_p}{2d_b}\left[1 - \frac{d_b^2 cos^2(\theta)}{d_p^2}\right] f_r \tag{4}$$

where subscripts BPO, BPI, C and BS stand for, respectively, Ball Passing Frequency Outer (ring), Ball Passing Frequency Inner (ring), Cage and Ball Spin frequency; n_b – number of rolling elements, d_p – pitch diameter, d_b- ball diameter, θ – contact angle and f_r– rotating frequency of the motor shaft.

Depending upon the requirements of load and speed, there are different types of bearings. Besides the mechanical issues of bearings, operating in the harsh marine conditions, bearings experience some other difficulties, which arise due to environmental issues. Here, contamination of bearing with dust, salt particles, and water is one issue; another issue is the deterioration of the lubricating oil. Due to poor lubrication, friction becomes greater, resulting in a higher temperature of bearing components. As a result, faster wear of bearing components takes place. Slowly, rings, rollers, and cages of the bearing will get damaged. When the bearing becomes damaged, then rotor eccentricity is experienced due to which more mechanical stress arises in the motor, resulting in damage to the motor (Tandon, Ramakrishna and Yadava, 2007). Bearing faults cause fluctuations in the current of the motor because of differences in the radial clearance between rotating shaft and stationary part, and relative motion between rotor and stator. Consequently, loading torque will vary, which ultimately causes variation in the phase, frequency, and current of the motor.

2.2 Broken rotor bar

Broken rotor bar occurs when the conductive rotor bars within the rotor cage get cracked or fully separated, either along the rotor bar length or from the rotor bars to the end ring assembly (Figure 2).

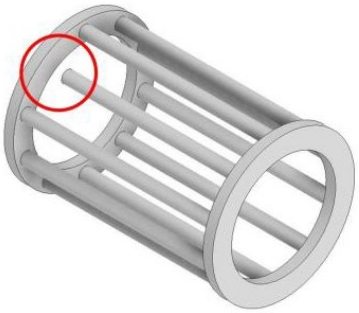


Figure 2. Broken rotor bar; (Source: Authors).

According to (Liang, Ali and Zhang, 2020) BRB account for about 8% of total analysed failures in induction motors. BRB problems usually occur due to mechanical and thermal stresses, such as regular on/off operations, loading conditions, corrosion, excessive vibrations, and thermal expansion. Moreover, BRB problems could arise from production defects, such as improper castings or end-ring connections. After the initial problem occurs, localized overheating and gradual damage to the rotor bar may follow (Mehrjou *et al.*, 2011). BRB problems usually occur due to mechanical and thermal stress factors, such as regular on-off operations, loading conditions, corrosion, excessive vibrations, and thermal expansion phenomena. Moreover, BRB problems could arise from production defects, such as improper castings or end ring connections. After the initial problem occurs, localized overheating and gradual damage to the rotor bar may follow (Čulić *et al.*, 2025). Preventing BRBs involves proper design, maintenance, and operation of the motor. Various methods for diagnosing BRB have been developed. One widely used technique is Motor Current Signature Analysis. Other techniques include zero sequence voltage analysis, vibration analysis, acoustic emission analysis, and flux based methods (Atta, Ibrahim and Gilany, 2022).

3. Detection methods

This chapter presents techniques for detecting faults in electrical machines, focusing on signal based diagnostic methods. It specifically covers MCSA and SFSA as reliable tools for identifying issues such as bearing faults and broken rotor bars.

3.1. Motor Current Signature Analysis

Fault identification in the induction motor is mainly based on choosing proper diagnostic methods and adequate knowledge of the working principle of those methods. One of the widely applied non-invasive method for fault detection is the Motor Current Signature Analysis. This method involves the analysis of the spectrum of the currents flowing through the stator of the induction motor (Mehrjou *et al.*, 2011). As per this technique, the current flowing through the motor is recorded by using current sensors such as current probe. These recordings are then digitized and analyzed using techniques like Fast Fourier Transform (FFT). Variations in operating conditions, such as load change, rotor imbalance, and mechanical vibration, cause modulation in the current signal, which acts as a warning signal for the upcoming faults. Despite being an easy and popular tool for industrial applications, the effectiveness of MCSA might be poor in the case of lower slip and simultaneous faults. For further insight into the application of MCSA in the presence of multiple fault, one may refer to the previous study conducted by the authors (Čulić et al., 2025). A malfunctioning bearing and a broken rotor bar cause fluctuations in the motor load, resulting in current variations and interruptions in the electromagnetic field. In particular, a BRB prevents current flow, and therefore no magnetic flux is produced along that bar. Consequently, there is an imbalance in the rotor's magnetic field and the creation of a rotating magnetic field in the opposite direction to the rotor's movement. This induces harmonic currents in the stator winding, which are superimposed on the stator current. The following frequencies are found in the stator current for the bearing fault case (Boudinar *et al.*, 2016):

$$f_{BF} = |f_s \pm k f_v| \quad k = 1, 2, 3, \ldots \tag{5}$$

where f_s is supply frequency, f_v is characteristics frequency depending of type of bearing fault (f_{BPO}, f_{BPI}, f_C or f_{BS}).

Specific frequency components for broken rotor bar fault in stator current are (Liang, Ali and Zhang, 2020):

$$f_{BRB} = (1 \pm 2ks)f_s \quad k = 1, 2, 3, \ldots \tag{6}$$

where f_s is supply frequency, s is slip of the induction motor.

The ability of MCSA for fault detection without direct contact with the motor makes it highly desirable for sectors aiming to minimise downtime. Among its advantages is the capability to detect faults even during normal operation. However, despite its success, MCSA has certain limitations. The accuracy of diagnosis may be affected by factors such as electrical noise, load torque variation, and complex motor configurations. False positives can result from rotor asymmetry or load torque variation, while false negatives may occur due to masking effects caused by load variation, low slip, etc. To increase diagnostic accuracy, it has become necessary to combine MCSA with other methods, including vibration testing, SFSA, and thermographic testing.

3.2. Stray flux signature analysis

Stray Flux Signature Analysis is another useful non-invasive method used to identify faults in induction motors without causing any damage to the motors. SFSA involves measuring stray magnetic flux from the motor housing (Figure 3). Although stray flux is unwanted electromagnetic interference, it contains information about the condition of the electromechanical system inside the motor, allowing faults to be detected by analysing changes in the features of the flux (Sabir, Ouassaid and Ngote, 2022). In actual implementations, stray flux is normally sensed using coil type sensors such as search coils, which are fitted externally to the frame of the motor. The sensors measure the leakage flux and produce a voltage output signal proportional to the magnetic flux density. The sensor output is digitized and tested with FFT to detect the existence of various harmonics due to the faulty operation of the motor.

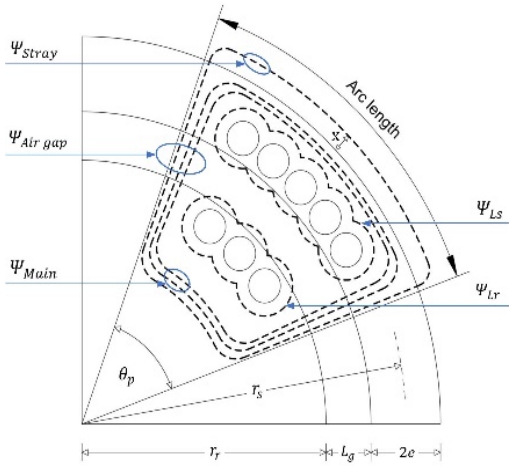


Figure 3. Illustration of stray flux; (Source:Koroglu et al., 2009).

In comparison to MCSA that requires electrical signatures from the power supply system for analysis, SFSA presents another viewpoint by focusing on the changing patterns of the magnetic fields. It is easy and economical to apply, since it only needs the presence of just one or two external sensors. Its success, however, highly depends on the correct placement of the sensors because it is very much influenced by the changes in the axial and radial leakage flux arising from the rotor imbalance or air gap eccentricity. Radial flux affects the machine axis while axial flux impacts the stator winding ends and the rotor rings (Figure 4)(Capolino *et al.*, 2019).

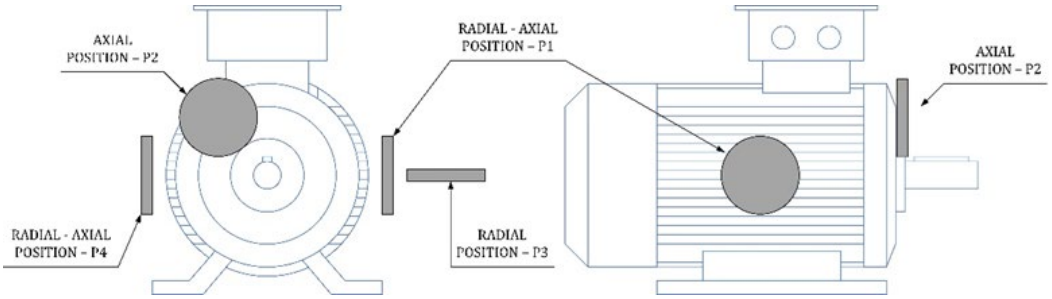


Figure 4. Coil sensor in different measurement positions; (Source: Authors).

The SFSA can detect not only electrical but also mechanical faults such as broken rotor bars and bearing faults. For example, in case of BRB, the symmetry of the magnetic field gets disturbed, resulting in the backward rotating field that includes unique harmonic frequencies. In other scenarios, more than one search coil is used to detect mechanical faults, especially those related to the bearings. Studies have revealed that certain fault conditions strengthen certain frequency components. (Iglesias-Martinez *et al.*, 2019). SFSA provides a number of advantages, in particular, providing the capability of real-time monitoring without any need to inspect inner elements of the motor. Combining this technique with the use of sophisticated processing methods, such as FFT, enables an accurate analysis of frequency bands corresponding to faults. The possible application of SFSA, in particular, for combined fault detection, has been mentioned in the authors' previous studies (Čulić *et al.*, 2025).

4. Experimental setup

The experimental methodology developed for this research involved creating a laboratory environment to accurately simulate faulty conditions in the marine induction motor and to perform non-invasive current and stray flux measurements. Steady state conditions were essential for these experiments, as they ensure reliable spectral analysis. The induction motor used for test was a Končar induction motor with a capacity of 0.55 kW, typical for small drives found aboard ships. It was coupled with a servo motor serving as the controllable load (Figure 5).

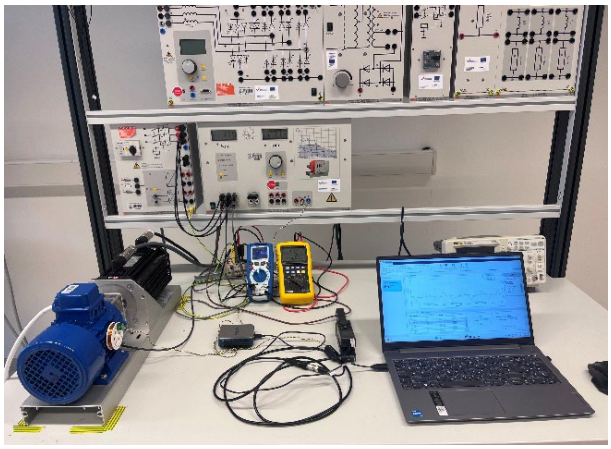


Figure 5. Test bench used in laboratory (Source: Author)

The servo motor's ability to control the load enabled constant operating conditions during the experiment. To ensure steady state operation, an ammeter was connected to the second phase (L2) and a voltmeter to the L1 and L2 phases. Faults were introduced through a series of steps. For the BRB fault, a precise hole was made in one of the aluminum rotor bars, effectively disconnecting the conductor circuit. The BF fault was implemented using a different approach, simulating a scenario involving severe deterioration of lubricant grease. Both faults were combined to create three motor fault conditions: a motor with BRB, a motor with BF, and a motor with both faults. In MCSA, a current sensor was connected to one phase of the motor power supply cable. In SFSA, a search coil, was used and attached to the motor body. The signals from both sensors were collected to a National Instruments datalogger (NI USB-6001). Before collecting data from each of the four motor states, a warm up period was used, during which the motor operated under load for an hour. This eliminated the effect of transient thermal states, as temperature changes could have affected the electrical signature. To achieve reliable results, a set of 50 measurements, each lasting 20 seconds, were collected for the healthy motor and for

each fault condition. The sampling frequency was set at 5,000 Hz, which was sufficient to capture all fault frequencies. All signal processing and analysis were performed offline using MATLAB software.

5. Results

Boxplots were used for the graphical representation of the results (Figure 5) and (Figure 6). For numerical comparison, the Wilcoxon signed rank test was used, as it does not assume normal distribution of the results. This test is paired, meaning that before and after states are compared for the same test object. The Wilcoxon signed rank test was performed in MATLAB using the function “p = signrank(x, y)”. A significance level of 5% was used.

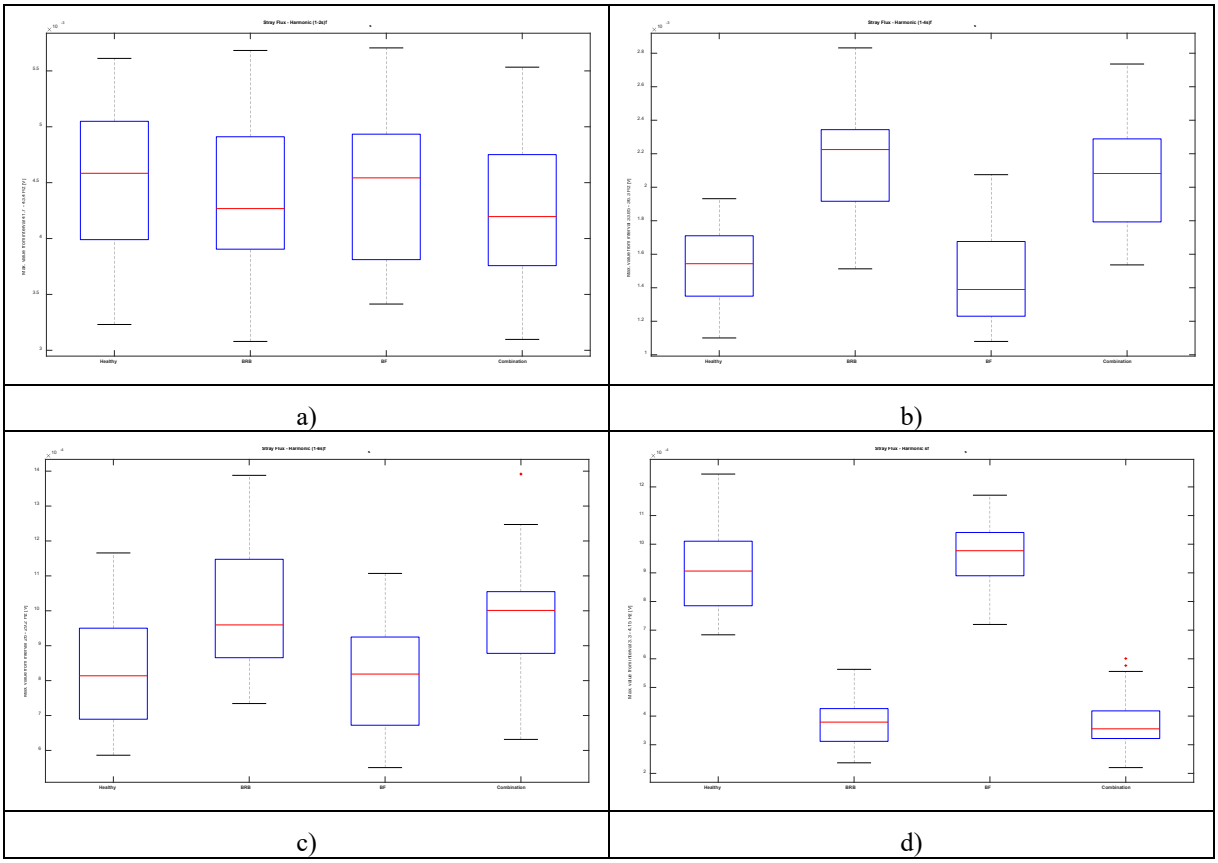
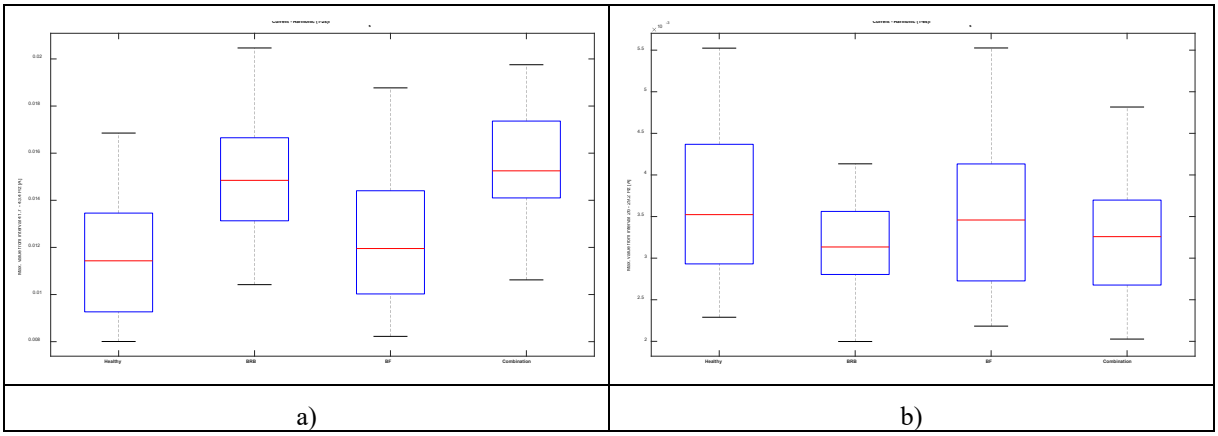
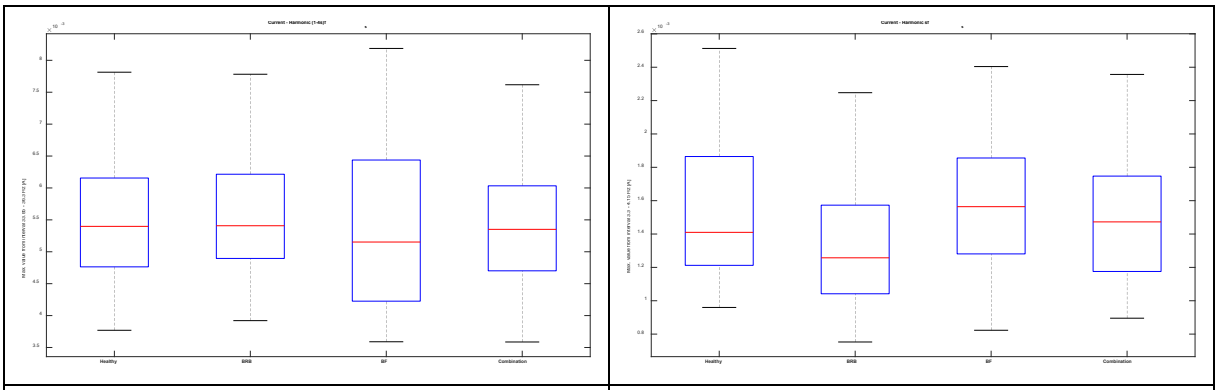


Figure 5: SFSA results (Source: Authors)





c) d)

Figure 6: MCSA results (Source: Authors)

In order to give a general description of the recorded signals, the time domain waveforms of stator current and coil voltage are presented. The signals were captured when the motor was in operation for 20 seconds. In the figures, the waveforms on the left are for the entire period of measurement, whereas those on the right depict the enlarged waveform for a short duration of time (10.0-10.1 seconds).

Figure 7 and 8 present the time-domain waveforms of the stator current and coil voltage measured under broken rotor bar and healthy operating conditions. In each figure, the upper plots correspond to the stator current, while the lower plots show the coil voltage. The time domain signals are the responses of the machine with the given operating conditions, and will serve as inputs for further signal analysis and feature extraction.

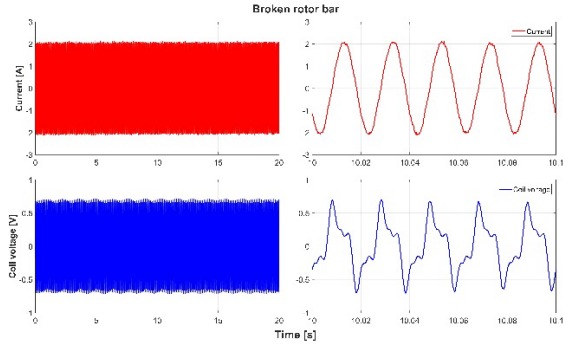


Figure 7: Time-domain waveforms of the stator current and coil voltage under the broken rotor bar condition.

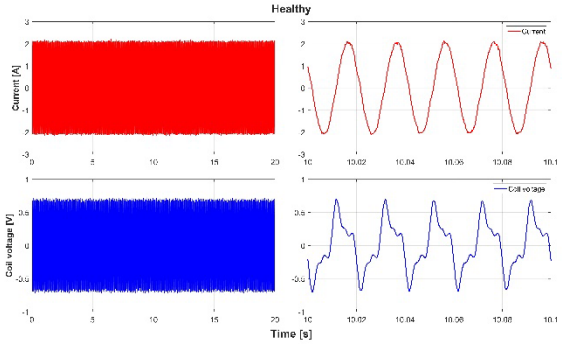


Figure 8: Time-domain waveforms of the stator current and coil voltage under the healthy operating condition.

Table 1 shows the results of the Wilcoxon signed rank test. All p-values below 0.05 are highlighted in yellow. Values below the 5% significance level indicate a statistically significant difference between motor states.

Table 1. Results of the Wilcoxon signed rank test

	Stray Flux				Current			
Harmonic	(1-2s)fs	(1-4s)fs	(1-6s)fs	sfs	(1-2s)fs	(1-4s)fs	(1-6s)fs	sfs
	Wilcoxon signed rank test p-value							
Healthy – BRB	$2.25 \cdot 10^{-1}$	$1.22 \cdot 10^{-9}$	$1.36 \cdot 10^{-5}$	$7.55 \cdot 10^{-10}$	$1.72 \cdot 10^{-7}$	$3.32 \cdot 10^{-1}$	$7.15 \cdot 10^{-4}$	$0.16 \cdot 10^{-1}$
Healthy – BF	$6.67 \cdot 10^{-1}$	$1.38 \cdot 10^{-1}$	$5.65 \cdot 10^{-1}$	$7.40 \cdot 10^{-3}$	$1.33 \cdot 10^{-1}$	$8.35 \cdot 10^{-1}$	$1.78 \cdot 10^{-1}$	$2.04 \cdot 10^{-1}$
Healthy – Com.	$0.26 \cdot 10^{-1}$	$3.17 \cdot 10^{-9}$	$9.59 \cdot 10^{-6}$	$7.55 \cdot 10^{-10}$	$1.06 \cdot 10^{-8}$	$7.24 \cdot 10^{-1}$	$0.13 \cdot 10^{-1}$	$8.43 \cdot 10^{-1}$
BRB – BF	$4.78 \cdot 10^{-1}$	$1.75 \cdot 10^{-9}$	$2.29 \cdot 10^{-6}$	$7.55 \cdot 10^{-10}$	$1.56 \cdot 10^{-5}$	$2.18 \cdot 10^{-1}$	$0.20 \cdot 10^{-1}$	$7.41 \cdot 10^{-4}$
BRB – Com.	$3.32 \cdot 10^{-1}$	$3.32 \cdot 10^{-1}$	$9.50 \cdot 10^{-1}$	$4.78 \cdot 10^{-1}$	$4.78 \cdot 10^{-1}$	$3.46 \cdot 10^{-1}$	$2.94 \cdot 10^{-1}$	$0.42 \cdot 10^{-1}$
BF – Com.	$0.67 \cdot 10^{-1}$	$2.10 \cdot 10^{-9}$	$1.72 \cdot 10^{-6}$	$7.55 \cdot 10^{-10}$	$3.85 \cdot 10^{-6}$	$8.13 \cdot 10^{-1}$	$2.07 \cdot 10^{-1}$	$2.56 \cdot 10^{-1}$

6. Conclusion

In this study, the possibility of detecting broken rotor bar faults, bearing faults, and their combination is investigated using stray flux and current measurement approaches. The study was conducted under steady-state conditions. As fault indicators, four harmonics were used within the frequency interval 0–50 Hz. The results show that, in the case of stray flux and current measurements, none of the harmonics used can statistically differentiate all possible combinations of motor states. The closest candidate is obtained with stray flux measurement using the harmonic sfs. From the boxplots and Wilcoxon test, it is evident that this harmonic cannot statistically differentiate between the broken rotor bar fault and the combination of faults. Furthermore, the results show that with current measurement and the harmonic (1–4s)fs, there is absolutely no differentiation between motor states. Future work will focus on investigating more harmonics over a wider interval.

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Assessing Human-Centered Digital Decision Support Systems in VTS Operations: A Pilot Study

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Abstract: Digitalization in the maritime sector is playing an increasingly important role in supporting safe operations. Digital decision support systems, particularly those used in Vessel Traffic Service (VTS) operations, aim to increase operators' situational awareness and reduce human error. However, the impact of these systems on human factors needs to be evaluated from a human-centered perspective. The study aims to examine the situational awareness and perceived workload of VTS operators and maritime professionals in the context of digital decision support systems. The research utilized Endsley's three-level situational awareness model and the NASA-TLX workload scale. A survey was administered to actively working VTS operators (n = 46). Although the relatively small sample size limits generalizability, the results suggest that digital VTS systems generally support operators' situational awareness, but in some cases, they may also increase mental workload and time pressure. These findings underscore the critical importance of developing digital decision support systems in VTS operations in accordance with human-centered design principles for safe and sustainable maritime operations. Additionally, the role of digital systems in maritime education warrants consideration alongside human factors.

Keywords: VTS; digital decision support systems; situational awareness; workload; human-centered design

1. Introduction

The maritime sector has undergone a profound transformation in recent years, driven by rapid advancements in digital technologies and increasing demands for safety, efficiency, and sustainability. The integration of digitalization into maritime operations often referred to as the concept of "smart shipping" or "digital oceans" has led to the widespread adoption of advanced decision-support systems, particularly within Vessel Traffic Services (VTS). These systems are designed to enhance navigational safety by improving operators' situational awareness, optimizing traffic flow, and minimizing the likelihood of human error (Hoff and Bashir, 2015; Sharma et al., 2025; European Maritime Safety Agency, 2023).

VTS systems represent a critical component of modern maritime traffic management, functioning as shore-based monitoring and advisory systems that support vessel navigation in congested or high-risk waters. With the incorporation of digital decision-support tools, including real-time data integration, predictive analytics, and automated alerts, VTS operations have become increasingly dependent on human–machine interaction. While these technological developments offer significant benefits, they also introduce new challenges related to human factors, particularly in terms of cognitive workload, trust in automation, and the maintenance of situational awareness (Fan et al., 2020; Grech et al., 2022).

Situational awareness (SA), as conceptualized by Endsley's Situational Awareness Model, is widely recognized as a fundamental determinant of performance in complex and dynamic operational environments. In maritime contexts, maintaining accurate perception, comprehension, and projection of traffic conditions is essential for safe decision-making. However, increasing levels of automation may both support and hinder situational awareness, depending on system design and operator interaction (Endsley, 2017; Parasuraman et al., 2000).

In parallel, operator workload has emerged as a critical factor influencing performance and safety. The NASA Task Load Index (NASA-TLX) is frequently used to assess perceived workload across multiple dimensions, including mental demand, time pressure, and effort. Although digital systems are intended to reduce workload, poorly designed interfaces or excessive information flow may lead to cognitive overload, ultimately increasing the risk of human error (Hart, 2006; Bokau et al., 2025).

Another key dimension of human–automation interaction is trust in digital systems. Trust determines the extent to which operators rely on automated decision-support tools and directly affects operational outcomes. Both overreliance and underutilization of automation can create safety risks, highlighting the need for balanced and calibrated trust (Hoff and Bashir, 2015; Li and Yuen, 2024).

Despite the growing integration of digital technologies in VTS operations, existing research indicates that human factors remain the dominant contributors to maritime incidents. Communication breakdowns, reduced situational awareness, and increased cognitive workload continue to play a central role in accident causation, even in technologically advanced environments (Chauvin et al., 2013; European Maritime Safety Agency, 2023). While prior studies have individually examined situational awareness or workload in maritime contexts, few have simultaneously evaluated both constructs within a unified analytical framework specific to VTS digital environments. Moreover, existing literature predominantly focuses on navigational bridge operations rather than shore-based VTS settings, where human–machine interaction dynamics differ considerably. This gap is particularly significant given the rapid digitalization of VTS infrastructure. This underscores the importance of adopting a human-centered design approach in the development and implementation of digital decision-support systems.

In this context, the present study aims to evaluate the impact of digital decision-support systems on situational awareness and perceived workload among VTS operators and maritime professionals. By integrating established theoretical frameworks and empirical assessment tools, the study seeks to provide a comprehensive understanding of human–system interaction in digital maritime environments. The findings are expected to contribute to the development of safer, more efficient, and sustainable maritime operations aligned with human-centered design principles.

2. Methodology

Ethical approval for the study was obtained from the Social and Human Sciences Ethics Committee of Piri Reis University (Approval No: 64, Decision Date: 14/04/2026)

2.1. Study Design

This study was designed as a cross-sectional and descriptive research aiming to examine the effects of digital decision-support systems used in VTS on operators' situational awareness and perceived workload. A quantitative research approach was adopted, and a structured questionnaire was utilized to evaluate human–machine interaction.

The study is grounded in two well-established theoretical frameworks: Endsley's Situational Awareness Model (Endsley, 1995; Endsley, 2017) and the NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988; Hart, 2006).

2.2. Participants

A total of 46 VTS operators participated in the study. Participants were selected using a convenience sampling method based on voluntary participation. It is acknowledged that this sample size represents a limitation of the study, and findings should be interpreted with caution in terms of generalizability to broader VTS operator populations. Inclusion criteria: Active involvement in VTS operations, Experience with digital systems, Voluntary participation.

2.3. Data Collection Instrument

Data were collected using a structured questionnaire developed specifically for this study. The questionnaire development process involved item generation based on established theoretical frameworks, followed by expert review by three academic specialists in maritime human factors to assess content validity. A pilot test was subsequently conducted with five VTS operators to evaluate item clarity and face validity, after

which minor wording adjustments were made. Construct validity was supported by the reliability analyses reported in Section 3.3. The questionnaire consisted of four main sections:

2.3.1. Demographic and Professional Information

This section included variables such as: Years of experience as a VTS operator (0–2, 3–5, 6–10, ≥10 years) Frequency of digital system usage (rarely, occasionally, frequently, continuously)

2.3.2. Situational Awareness Scale

Situational awareness was measured using a 6-item scale based on Endsley's Situational Awareness Model (Endsley, 1995; Endsley, 2017). The scale covered: Perception of vessel traffic, Clarity of information presentation, Comprehension of the current situation, Risk awareness, Projection of future traffic conditions, Responses were rated on a 7-point Likert scale (1 = Strongly Disagree, 7 = Strongly Agree).

2.3.3. Workload Scale (NASA-TLX)

Perceived workload was assessed using a 6-item scale based on NASA Task Load Index (NASA-TLX) (Hart and Staveland, 1988; Hart, 2006). The scale included the following dimensions: Mental demand, Temporal demand, Effort, Frustration level, Perceived performance, Physical demand Each item was rated on a 7-point Likert scale (1 = Very Low, 7 = Very High).

2.3.4. Open-Ended Question

Participants were also asked an open-ended question to provide suggestions on how digital VTS systems could be improved to enhance safer and more effective decision-making processes.

2.4. Data Collection Procedure

The questionnaire was administered online to ensure accessibility and ease of participation. Participants were informed about the purpose of the study, and anonymity and confidentiality were guaranteed. The average completion time of the survey was approximately 10–15 minutes. Participation was entirely voluntary, and informed consent was obtained from all participants prior to data collection.

2.5. Data Analysis

The collected data were analyzed using statistical software (e.g., SPSS). The analysis included descriptive statistics (mean, standard deviation, frequency, and percentage), reliability analysis using Cronbach's alpha with an acceptable threshold of ≥ 0.70 (Nunnally and Bernstein, 1994), and Pearson correlation analysis to examine the relationships between variables (Field, 2018). In addition, responses to the open-ended question were analyzed using qualitative content analysis. A significance level of $p < 0.05$ was considered statistically significant.

3. Results

3.1. Participant Characteristics

A total of n = 46 VTS operators participated in the study. The distribution of participants based on professional experience and digital system usage is presented as follows. In terms of professional experience, 17.4% (n = 8) had 0–2 years of experience, 26.1% (n = 12) had 3–5 years, 30.4% (n = 14) had 6–10 years, and 26.1% (n = 12) had 10 years or more. Regarding the frequency of digital system use, 4.3% (n = 2) reported using such systems rarely, 13.0% (n = 6) occasionally, 34.8% (n = 16) frequently, and 47.8% (n = 22) continuously. These findings indicate that the majority of participants were experienced operators who regularly engaged with digital VTS systems.

3.2 Descriptive Statistics

Descriptive statistics for situational awareness and workload dimensions among the 46 participants are presented in Table 1.

Table 1. Descriptive Statistics of Main Variables (n = 46)

Variable	N	Mean	Std. Deviation
Situational Awareness	46	5.59	0.87
Mental Demand	46	4.78	1.07
Temporal Demand	46	5.20	1.20
Effort	46	4.59	0.98
Frustration	46	4.00	1.23
Performance	46	5.35	0.90
Physical Demand	46	3.20	1.13

The results indicate that situational awareness scores were relatively high, suggesting that digital VTS systems effectively support operators' ability to perceive, interpret, and anticipate maritime traffic conditions. In contrast, mental demand (M = 4.78) and temporal demand (M = 5.20) were observed at moderate to high levels, indicating that operators experience considerable cognitive and time- related pressure while using digital systems. Notably, frustration (M = 4.00) and physical demand (M = 3.20) were relatively lower, suggesting that workload is primarily cognitive rather than physical in nature.

3.3. Reliability Analysis

Internal consistency of the scales was assessed using Cronbach's alpha based on data obtained from 46 participants. The Situational Awareness Scale demonstrated a Cronbach's alpha coefficient of $\alpha = 0.89$, while the Workload Scale (NASA-TLX adapted) showed a coefficient of $\alpha = 0.86$. Both scales exhibited good internal consistency, indicating that the measurement instruments used in this study are reliable for assessing human factors in VTS environments (Table 2, Table 3).

Table 2. Item–Total Statistics (Situational Awareness Scale)

Item	Corrected Item–Total Correlation	Cronbach's Alpha if Item Deleted
SA1	0.68	0.84
SA2	0.71	0.83
SA3	0.73	0.82
SA4	0.69	0.84
SA5	0.66	0.85
SA6	0.70	0.83

Table 3. Item–Total Statistics (Workload Scale)

Item	Corrected Item–Total Correlation	Cronbach's Alpha if Item Deleted
WL1 (Mental)	0.65	0.81
WL2 (Temporal)	0.67	0.80
WL3 (Effort)	0.64	0.82
WL4 (Frustration)	0.61	0.83
WL5 (Performance)	0.66	0.81
WL6 (Physical)	0.59	0.83

All items demonstrated acceptable corrected item–total correlations (> 0.50), indicating good item consistency. Furthermore, no substantial increase in Cronbach's alpha was observed when any item was deleted, suggesting that all items contributed meaningfully to the overall scale reliability.

3.4. Correlation Analysis

Pearson correlation analysis was conducted to examine the relationships between situational awareness, workload, and perceived performance among the 46 participants. The results are presented in Table 4.

Table 4. Correlations Between Variables (n = 46)

Variable	Column A	Column B
1. Situational Awareness	—	
2. Workload	-0.43*	—
3. Perceived Performance	0.47*	-0.33*

More specifically, situational awareness was negatively correlated with workload (r = -0.43, p= 0.003), while it showed a positive relationship with perceived performance (r = 0.47, p =0.001). Additionally, workload was negatively associated with perceived performance (r = -0.33, p = 0.025).

3.5. Regression Analysis

A linear regression analysis was conducted to examine the predictive effect of workload on situational awareness.

Table 5. Regression analysis predicting situational awareness

Predictor	B	SE	β	t	p
Constant	7.39	0.58	—	12.70	<0.001
Workload	-0.41	0.13	-0.43	-3.16	0.003

3.6. Group Comparisons

To examine the effects of professional experience and digital system usage frequency, one-way ANOVA analyses were conducted based on data obtained from 46 participants. A statistically significant difference was observed in situational awareness scores across experience groups ($F(3,42) = 3.18$, $p = 0.033$). Post-hoc comparisons (Tukey HSD) indicated that operators with ≥10 years of experience demonstrated significantly higher situational awareness levels compared to those with less than 5 years of experience. Similarly, digital system usage frequency had a significant effect on situational awareness ($F(3,42) = 3.52$, $p = 0.022$). Participants who reported continuous use of digital systems exhibited higher situational awareness scores compared to those with lower usage frequencies. In addition, a significant difference was found in temporal demand across usage groups ($F(3,42) = 3.74$, $p = 0.018$), with continuous users reporting higher levels of time pressure. This finding suggests that increased interaction with digital systems may enhance awareness while simultaneously elevating cognitive and temporal workload.

3.7. Qualitative Findings (Open-Ended Responses)

Qualitative data obtained from open-ended responses were analyzed using content analysis revealing three primary themes: system design, workload management, and training. Participants frequently emphasized the need for improvements in system design, particularly highlighting the importance of more user-friendly interfaces, simplified information presentation, and the reduction of visual clutter. These findings suggest that current digital VTS systems may impose unnecessary cognitive demands due to complex interface structures. Workload reduction emerged as another key concern. Respondents suggested that implementing more effective filtering mechanisms to eliminate irrelevant information and increasing the automation of repetitive tasks could significantly reduce cognitive burden and improve operational efficiency. Finally, participants highlighted the importance of training and adaptation processes. Simulation-based training and continuous professional

development were identified as essential for improving system familiarity and enhancing decision-making performance in digital maritime environments.

4. Discussion

The findings of this study provide a comprehensive and integrated understanding of the impact of digital decision-support systems in Vessel Traffic Services (VTS), demonstrating a complex interaction between performance enhancement and cognitive demand. The results clearly indicate that digital systems significantly improve situational awareness while simultaneously increasing mental and temporal workload. This dual effect reflects a critical issue in contemporary maritime operations, where digitalization enhances operational capabilities but also introduces new human-factor-related challenges rather than eliminating them (Alan and Beşikçi, 2025).

The relatively high levels of situational awareness observed among the 46 participants suggest that digital VTS systems effectively support operators in perceiving, interpreting, and projecting maritime traffic conditions. This finding is consistent with Endsley's Situational Awareness Model, which emphasizes that accurate and timely information integration is fundamental for decision-making in dynamic environments (Endsley, 1995; Endsley, 2017). In line with previous studies, the integration of real-time data, visual interfaces, and predictive functionalities appears to facilitate higher levels of situational awareness in complex maritime settings (Sharma et al., 2025; Grech et al., 2022).

However, the results also demonstrate that these benefits are accompanied by increased cognitive demands. The moderate to high levels of mental and temporal workload observed in this study indicate that operators must continuously process large volumes of information under time pressure. This finding is consistent with recent research showing that digitalization and automation may simultaneously reduce manual workload while increasing cognitive workload (Crestelo Moreno and García Maza, 2026). The workload structure identified in this study aligns with the multidimensional framework of the NASA Task Load Index (NASA-TLX), where mental and temporal demands emerge as dominant factors (Hart and Staveland, 1988; Hart, 2006).

One of the most important contributions of this study is the identification of a statistically significant negative relationship between workload and situational awareness ($r = -0.43$, $p < 0.05$), which represents a medium effect size (Cohen, 1988). This was further supported by regression analysis showing that workload significantly predicts situational awareness ($\beta = -0.43$, $p < 0.01$, $R^2 = 0.185$). These findings suggest that increasing cognitive demand may directly impair operators' ability to maintain accurate situational awareness. This result is strongly supported by cognitive load theory and human factors research, which emphasize that excessive workload reduces attentional capacity and decision-making performance in complex systems (Wickens, 2008; Crestelo Moreno and García Maza, 2026). In safety-critical environments such as VTS operations, this relationship is particularly important, as reduced situational awareness may increase the risk of operational errors.

The positive relationship between situational awareness and perceived performance ($r = 0.47$, $p < 0.01$) further highlights the central role of awareness in operational effectiveness. Operators with higher situational awareness are more capable of making accurate and timely decisions, which directly contributes to improved performance outcomes. This finding is consistent with previous research demonstrating that situational awareness is a key predictor of performance in high-risk and technology-driven environments (Endsley, 2017; Grech et al., 2022).

The group comparison analyses provide additional insights into the role of experience and system usage. More experienced operators demonstrated significantly higher situational awareness levels, suggesting that accumulated operational knowledge and pattern recognition abilities enhance cognitive processing efficiency. At the same time, operators who reported continuous use of digital systems exhibited both higher situational awareness and increased temporal demand. This finding suggests that while familiarity with digital systems enhances performance, it may also increase perceived responsibility and time pressure. These results highlight the importance of balancing system use with effective workload management strategies.

The qualitative findings further support and enrich the quantitative results. Participants consistently emphasized issues related to interface complexity, information overload, and usability challenges. These insights are consistent with established human–computer interaction principles, which suggest that poorly designed interfaces can increase cognitive burden and reduce system effectiveness (Norman, 2013). The need

for improved information filtering and automation of repetitive tasks reflects the importance of reducing unnecessary cognitive load in high-demand environments. Furthermore, the emphasis on simulation-based training and continuous professional development highlights the need for adaptive learning processes in response to rapidly evolving digital technologies. This is consistent with maritime safety literature emphasizing the role of training in reducing human error and improving system performance (Chauvin et al., 2013).

Taken together, these findings indicate that the effectiveness of digital VTS systems is not solely dependent on technological advancement but is strongly influenced by how these systems are designed and integrated with human operators. A human-centered approach that prioritizes usability, cognitive ergonomics, and adaptive system design is essential to maximize the benefits of digitalization while minimizing its potential risks. Without such an approach, the advantages of digital technologies may be offset by increased cognitive workload and diminished operator performance.

In this context, this study contributes to the growing body of literature by providing an integrated evaluation of situational awareness and workload within a single analytical framework. The findings highlight that improving maritime safety in digital environments requires not only technological innovation but also a systematic consideration of human factors. Achieving an optimal balance between situational awareness and workload emerges as a key requirement for ensuring safe, efficient, and sustainable VTS operations.

5. Conclusion

This study provides a comprehensive human-centered evaluation of the impact of digital decision support systems on situational awareness and perceived workload among Vessel Traffic Services (VTS) operators. The findings clearly demonstrate that digital systems significantly enhance operators' ability to perceive, interpret, and anticipate maritime traffic conditions. However, this improvement is accompanied by increased cognitive demands, particularly in terms of mental and temporal workload.

The statistical results further reveal a significant negative relationship between workload and situational awareness, supported by both correlation and regression analyses ($r = -0.43$; $\beta = -0.43$, $R^2 = 0.185$). These analyses demonstrate that increased cognitive load not only coexists with but also directly predicts reductions in situational awareness levels. At the same time, the positive association between situational awareness and perceived performance highlights the critical role of awareness in ensuring effective operational decision-making.

In addition, group comparisons show that professional experience and continuous system use positively influence situational awareness, although higher system engagement is also associated with increased time pressure. This highlights a key trade-off in digital maritime environments: while technological advancements enhance operational awareness and performance, they may simultaneously introduce additional cognitive burdens.

From a practical perspective, the findings emphasize that the effectiveness of digital VTS systems depends not only on technological sophistication but also on their alignment with human cognitive capabilities. Systems that fail to consider human-centered design principles may inadvertently reduce performance despite their advanced functionalities.

Several limitations of this study should be acknowledged. The relatively small sample size ($n = 46$) constrains the generalizability of the findings to broader VTS operator populations. Future studies should employ larger and more diverse samples across different geographic contexts. Additionally, the cross-sectional research design limits causal inference, and longitudinal approaches would be valuable in examining how operator experience with digital systems evolves over time. Accordingly, future developments in maritime digitalization should prioritize human-centered interface design, intelligent information filtering, adaptive automation strategies, and continuous, simulation-based training programs.

In conclusion, ensuring safe, efficient, and sustainable maritime operations requires an integrated approach that combines technological innovation with a systematic understanding of human factors. This study contributes to the literature by demonstrating that optimizing the balance between situational awareness and cognitive workload is essential for maximizing the effectiveness of digital transformation in maritime environments.

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Opportunities and Challenges in Implementing Integrated Fisheries Control Systems

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Abstract: Sustainable fisheries management requires robust regulatory frameworks supported by advanced technological systems capable of monitoring, analysing, and enforcing fishing activity at sea. The forthcoming EU Regulation 2025/2196 introduces a comprehensive transformation of fisheries control, including new Vessel Monitoring System (VMS) requirements, digital logbooks, automated data exchange, and enhanced responsibilities for masters, shipowners, and Member State control centres. This paper examines the regulatory changes and evaluates emerging technologies—satellite communications, wireless sensor networks, GNSS, artificial intelligence, image processing, and secure data infrastructures—that will underpin a future human centred digital ocean. Drawing on literature from 2010 to 2024, the study identifies opportunities and challenges in implementing integrated fisheries control systems capable of supporting sustainable blue economy growth while ensuring compliance, transparency, and operational efficiency.

Keywords: Vessel Monitoring System; Fishing Effort, Marine Protected Areas, Global Navigation Satellite Systems, Wireless Sensor Networks, Satellite Communications

1. Introduction

Fisheries control systems have evolved significantly over the past two decades, driven by the need to protect marine ecosystems, ensure food security, and support the economic viability of coastal communities. Overfishing, illegal, unreported, and unregulated (IUU) fishing, and climate driven changes in species distribution have intensified the demand for accurate, real-time monitoring of fishing activities (FAO, 2022).

The European Union has progressively strengthened its fisheries governance framework, culminating in (EU Regulation 2196, 2025), which mandates a fully digital, interoperable, and data driven control system across all Member States. This regulation requires new technological capabilities on board fishing vessels, in national control centres, and within EU level data exchange infrastructures.

Simultaneously, rapid advances in satellite communications, GNSS, wireless sensor networks, and artificial intelligence have created unprecedented opportunities for real time monitoring, automated compliance verification, and improved decision making for fishers, authorities, and policymakers.

This paper expands the abstract provided by analysing the regulatory framework, reviewing relevant literature, and evaluating emerging technologies that will shape the future of fisheries control.

2. Literature Review (2010-2024)

2.1. Evolution of Fisheries Monitoring and Control Systems

Portugal initiated the VMS project in 1988 by developing an innovative Blue Box for fishing activities, integrating GPS and Inmarsat Standard-C with standalone batteries and the capability to exchange fax messages with a GIS control centre in the Ministry of Fisheries. This system enabled continuous monitoring of vessels

and was connected to other Member State control centres (Portugal, 1988; Vítor, 1993; Vítor, 1997; Vítor, 1999; Vítor, 2000), as illustrated in figure 1 – Monitoring of Fishing Activities System.

The success of the MONICAP project led to a profound transformation in fisheries monitoring across the European Union. All Member States were subsequently required to implement fisheries monitoring through a VMS system using satellite-based positioning and communication technologies, employing the so-called Blue Box.

(EC Regulation 2244, 2003) established detailed rules for the operation of satellite-based VMS systems by EU Member States. The regulation applied to fishing vessels exceeding 18 metres in overall length from 1 January 2004, and to vessels exceeding 15 metres from 1 January 2005.

VMS has remained a cornerstone of fisheries control since the early 2000s. Recent studies highlight the increasing integration of VMS with AIS to improve spatial resolution and reduce data gaps (Natale et al., 2015; Russo et al., 2020). AIS-based fishing-activity detection using machine learning has also become a major research area (Kroodsma et al., 2018).

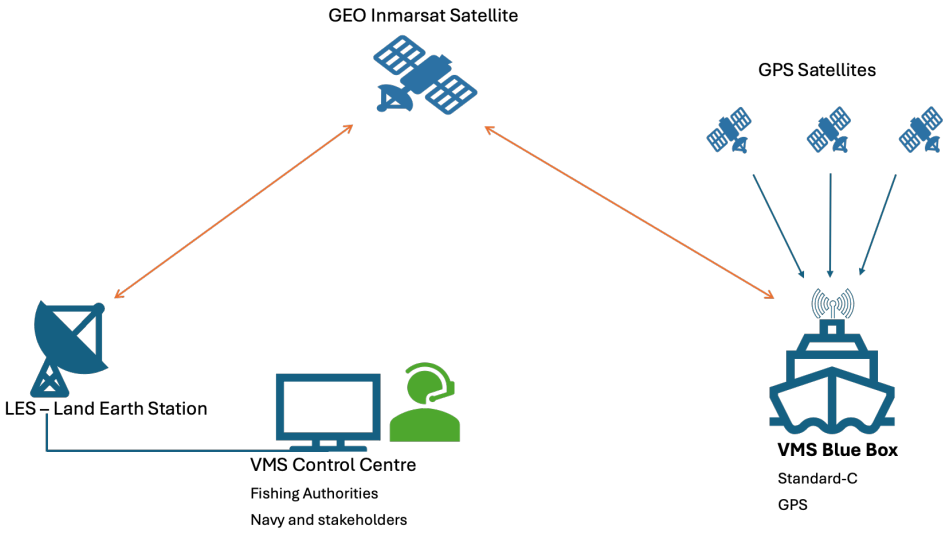


Figure 1- Monitoring of Fishing Activities System

The last decade has seen a profound transformation in fisheries monitoring systems, driven by technological innovation, regulatory pressure, and the increasing availability of high-resolution spatial data. Traditional Vessel Monitoring Systems (VMS), introduced in the late 1990s, have evolved from low frequency position reporting tools into integrated digital platforms capable of supporting real time compliance monitoring, automated data validation, and advanced analytics (Natale et al., 2015; Hintzen et al., 2012). The shift toward a human centred digital ocean reflects a broader trend toward data driven governance, where fishers, authorities, and researchers rely on interoperable digital infrastructures to support sustainable resource management (FAO, 2022).

The literature consistently highlights the need for higher temporal resolution, greater positional accuracy, and integration of multiple data sources (AIS, VMS, REM, sensor networks) to improve the reliability of fishing effort estimation and enforcement. These themes are reinforced by recent EU regulatory developments, including Regulation 2025/2196, which mandates full digitalisation of fisheries control systems.

2.2. Vessel Tracking technologies: VMS, AIS and VDES

AIS has become a critical complement to VMS, offering higher reporting frequency and richer contextual information (Russo et al., 2020). Studies such as Kroodsma et al. (2018) demonstrate the global potential of AIS for detecting fishing activity using machine learning classification models. However, AIS is not mandatory for all fishing vessels, and its susceptibility to intentional disabling or spoofing limits its enforcement reliability.

The 2025 study by Rufino (Rufino, 2025) provides a pivotal contribution by quantifying the bias introduced by low frequency VMS reporting. Rufino demonstrates that long reporting intervals can significantly

distort estimates of fishing effort, vessel speed profiles, and spatial footprint. Low temporal resolution can lead to substantial underestimation of fishing activity, particularly in mixed gear fisheries where manoeuvring patterns are complex.

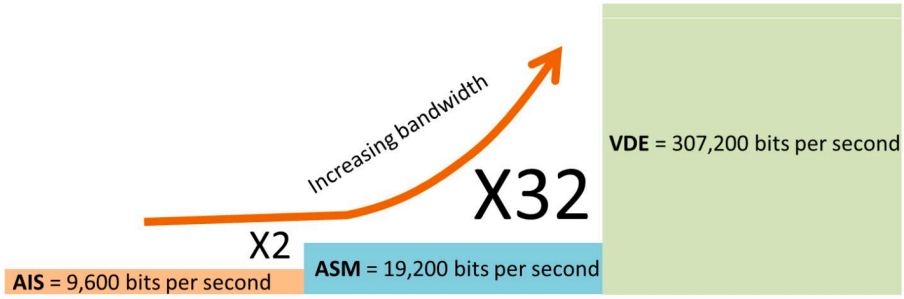


Figure 2 – Increasing bit rates in VDES evolution

Source: IALA Guideline G1117 (IALA, 2020)

The IALA Guideline G1117 introduces the VHF Data Exchange System (VDES) as a major evolution beyond AIS as in figure 2 – Increasing bit rates in VDES evolution. VDES integrates AIS, VDE Terrestrial, and VDE Satellite, offering higher bandwidth, two-way communication, and global satellite coverage. For fisheries control, VDES enables more frequent position reporting, transmission of REM data, real time alerts, and secure encrypted channels for enforcement authorities.

2.3. Remote Electronic Monitoring (REM)

The Technical Guidelines for REM in EU Fisheries provide a comprehensive framework for the deployment of onboard cameras, gear sensors, and data logging systems, example of figure 3 – REM proposed solution by EFCA. REM is increasingly recognised as a cornerstone technology for monitoring discards, verifying catch composition, ensuring compliance with landing obligations, and supporting stock assessment models. AI based image processing can achieve high accuracy in species identification, enabling automated logbook generation and reducing the burden on fishers (Park et al., 2020).

The REM guidelines specify minimum camera resolution, sensor placement standards, data encryption requirements, secure upload protocols, and audit procedures. These specifications align with broader EU digitalisation efforts, ensuring interoperability with VMS, AIS, and national control centre databases.

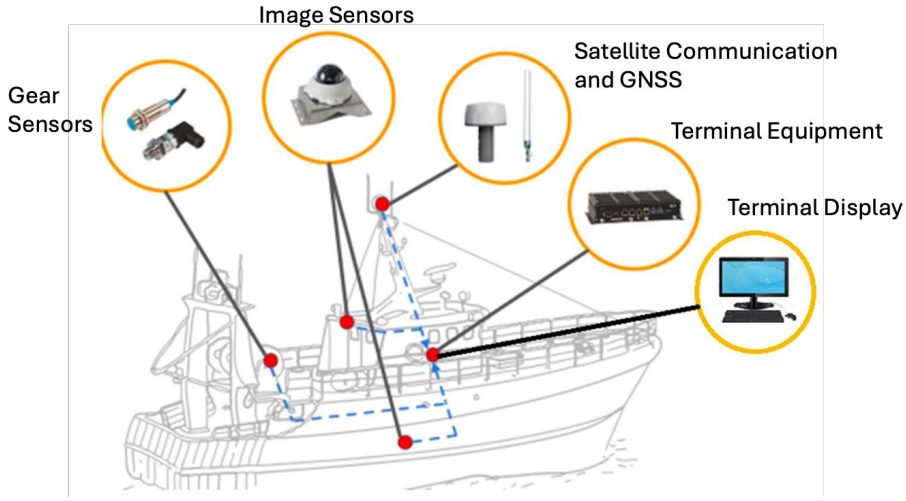


Figure 3- REM proposed solution by EFCA Source: (EFCA, 2019)

2.4. Fishing Effort Estimation and Spatial Analysis

Fishing effort is a central metric in fisheries science and management. Recent studies integrate VMS/AIS'S trajectories, gear specific activity signatures, environmental variables, and habitat models. Hintzen

et al. (2012) pioneered methods for reconstructing fishing tracks from sparse VMS data, while Piroddi et al. (2021) emphasised ecosystem-based approaches that incorporate trophic interactions and habitat impacts.

Rufino's (2025) findings reinforce earlier concerns about bias in fishing effort estimation. Low frequency data can misclassify fishing vs. steaming, distort spatial footprints, and underestimate interactions with sensitive habitats. Monitoring compliance within MPAs requires high resolution spatial data. Guardone et al. (2022) demonstrate that satellite-based monitoring significantly improves detection of illegal incursions.

2.5 Data Quality, Reporting, and Member State Performance

The Synopsis Report (Council Regulation (EC) No. 1224, 2009), provides a detailed assessment of Member State performance in fisheries data reporting. Key findings include persistent inconsistencies in logbook data, delays in reporting, gaps in VMS coverage, and variability in control centre capabilities. The report highlights the need for standardised data formats, automated validation systems, and improved cross border data exchange.

2.6 Satellite Communications and Connectivity

The emergence of LEO satellite networks has revolutionised maritime connectivity. These systems provide low latency and high bandwidth, enabling real time REM uploads, high frequency VMS reporting, and cloud-based AI processing (Farrington et al., 2023). VDES Satellite complements LEO systems by providing a regulated, maritime specific communication channel.

On March 30, 2026, Portugal successfully launched four LEO Satellites of Lusíada constellation for maritime navigation services, AIS/VDES communications services and earth observation expected fully operational by 2027 with 12 satellites. Launch also included two additional satellites from the Portuguese Air Force a LEO SAR (Synthetic Aperture Radar) satellite and an optical satellite (VHR Light NexGen) strengthening the Atlantic Constellation.

2.7 Wireless Sensor Networks and IoT in Fisheries

Wireless Sensor Networks (WSNs) are increasingly used for gear monitoring, catch estimation, and environmental sensing. Their robustness in harsh marine environments has been demonstrated in multiple studies, and their integration with IoT platforms allows for automated reporting and improved traceability (Xu et al., 2014; Vítor et al., 2023).

2.8 Artificial Intelligence and Image Processing

AI and computer vision enable automated species identification, bycatch detection, fishing activity classification, and anomaly detection (Russo et al., 2020; Fernandes et al., 2020). These capabilities are essential for REM systems, which rely on onboard cameras and sensors to document fishing operations (Park et al., 2020).

2.9 Secure Data Architectures, Interoperability and cybersecurity

Blockchain based traceability systems and cloud edge hybrid architectures are emerging as solutions for secure, tamper proof fisheries data. Encryption, redundancy, and standardised APIs support the EU's requirement for secure, interoperable data exchange (Sylvester et al., 2021). Maritime sector also faces major cybersecurity challenges not only from ICT networks but also related with navigation, industrial control systems, satellite communications (Radar, GPS, ECDIS, AIS) that can be blocked, jammed or spoofed (Akpan et al., 2022).

3. EU Regulation 2025/2196: Requirements and Implications

(EU Regulation 2196, 2025) represents one of the most significant reforms of the European Union's fisheries control framework in more than a decade. It introduces a comprehensive set of rules governing access

to waters and resources, surveillance, inspection, enforcement, quota deduction, and the management of fishing effort. The regulation mandates a complete transition to digital reporting and data exchange, requiring Member States to modernise their control infrastructures and fishing vessels to adopt new onboard technologies. According to the regulation, "each Member State will exchange fishing activity data with the Commission and EFCA in a standardized way," underscoring the EU's commitment to interoperability and harmonisation.

A central component of the regulation is the updated VMS requirements, which now apply to all fishing vessels, regardless of size as in comparison of table 1 – EFCA summarized minimal requirements. Vessels must be equipped with tamper proof GNSS based tracking devices capable of continuous position reporting, integration with electronic logbooks, and automated alerts for events such as entry into MPAs or deviations from declared fishing patterns. The regulation reinforces the responsibilities of the master, who must ensure accurate digital logbook entries, submit prior notifications for landing and transshipment, and report equipment failures without delay.

Table 1 – EFCA summarized minimal requirements Source: (EFCA, 2019)

Segment	Fishing type	Vessel length	Gear type	Vessel type	Indicative minimum number of cameras[3]	Sensors								Estimated system cost[4]	Estimated installation cost	Annual running cost[5]
						GPS	Net drum activity	Winch activity	RSW tank temperature	Power block	Fish pump	Knive valve	Catch in net[6]			
REM01	Demersal Passive	< 12 m	Set nets, lines		2		X							€ 6,000	€ 1,000	€ 500
REM02		12 – 18m			4		X							€ 6,500	€ 2,000	€ 1,000
REM03		> 18 m			4		X							€ 6,500	€ 2,000	€ 1,000
REM04	Demersal Active	< 12 m	Trawls		4			X						€ 6,500	€ 2,000	€ 1,000
REM05		12 – 18m			4			X						€ 6,500	€ 2,000	€ 1,000
REM06		18 – 24 m			5			X					X	€ 6,800	€ 2,500	€ 1,000
REM07		> 24 m			5			X					X	€ 6,800	€ 2,500	€ 1,000
REM08	Pelagic Active	< 12 m			2			X			X			€ 6,300	€ 1,000	€ 750
REM09		12 – 24m			4	X		X			X		X	€ 6,800	€ 2,000	€ 1,500
REM10		> 24 m			4			X			X		X	€ 8,000	€ 2,500	€ 1,500
REM11		12 – 24m		RSW	4			X	X		X	X	X	€ 8,000	€ 2,000	€ 1,500
REM12		> 24 m		RSW	4			X	X		X	X	X	€ 8,000	€ 3,000	€ 1,500
REM13		> 24 m		Freezers	8			X	X		X		X	€ 9,000	€ 3,000	€ 2,500
REM14		12 – 24m	Purse seine	RSW	4				X	X	X	X		€ 8,000	€ 2,500	€ 1,500
REM15		> 24 m		RSW	4				X	X	X	X		€ 8,000	€ 3,000	€ 1,500
REM16	Pelagic Passive	All	Long liner		3		X							€ 6,500	€ 2,000	€ 1,000

Member State control centres must implement real time data validation systems, maintain redundant and secure databases, and adopt automated risk analysis tools capable of identifying suspicious behaviour. They must also ensure seamless interoperability with EFCA and other Member States. These requirements address long standing issues identified in the Synopsis Report (Council Regulation (EC) No. 1224, 2009), including inconsistencies in reporting and variability in national control capabilities.

4. Technological Solutions for Future Fisheries Control

The technological landscape underpinning modern fisheries control is evolving rapidly, driven by advances in satellite communications, sensor networks, artificial intelligence, and secure data infrastructures. Global Navigation Satellite Systems (GNSS), including GPS, Galileo, GLONASS, and BeiDou, now provide highly accurate and reliable positioning data essential for VMS operations. Galileo's Public Regulated Service (PRS) offers encrypted and resilient positioning capabilities that can support enforcement authorities in detecting tampering or spoofing attempts (Bousquet et al., 2021). These positioning technologies form the backbone of the EU's digital monitoring framework, enabling precise tracking of vessel movements and supporting the reconstruction of fishing activity patterns.

Satellite communications have undergone a major transformation with the emergence of Low Earth Orbit (LEO) constellations such as Starlink, OneWeb, and Iridium Certus. These systems provide high bandwidth, low latency connectivity even in remote ocean regions, enabling real time transmission of VMS data, Remote Electronic Monitoring (REM) footage, and other operational information. When combined with the VHF Data Exchange System (VDES), as described in IALA Guideline G1117 (IALA, 2020), the result is a hybrid communication architecture capable of supporting both terrestrial and satellite-based data exchange. VDES enhances the traditional AIS system by offering greater bandwidth, two-way communication, and improved resilience, making it particularly suitable for high frequency reporting and the transmission of REM data. This

integration of LEO satellites and VDES is expected to play a central role in achieving the EU's vision of a human centred digital ocean.

Wireless sensor networks (WSNs) and Internet of Things (IoT) technologies are also becoming increasingly important in fisheries control. These systems enable continuous monitoring of gear deployment, catch weight, and environmental parameters such as temperature, salinity, and dissolved oxygen. Their robustness in harsh marine environments has been demonstrated in multiple studies, and their integration with onboard IoT platforms allows for automated reporting and improved traceability (Xu et al., 2014) throughout the supply chain. When combined with GNSS and satellite communications, WSNs provide a rich, multi layered dataset that enhances the accuracy of fishing effort estimation and supports ecosystem-based management approaches.

Artificial intelligence and image processing technologies are transforming the way fisheries data is collected and analysed. Deep learning models can now identify fish species with high accuracy, detect bycatch events, and classify fishing activity based on vessel movement patterns. These capabilities are essential for the effective implementation of REM systems, which rely on onboard cameras and sensors to document fishing operations. AI assisted analysis reduces the workload on human reviewers, increases the consistency of compliance assessments, and enables near real time feedback to fishers and authorities. Furthermore, anomaly detection algorithms can identify suspicious behaviour, such as abrupt course changes or prolonged periods of inactivity, which may indicate potential non-compliance. AI and image processing technologies are transforming fisheries data collection and analysis, enabling automated species identification, bycatch detection, and fishing activity classification (Park et al., 2020). These capabilities are essential for REM systems, which rely on onboard cameras and sensors to document fishing operations.

Finally, secure data architectures are critical to ensuring the integrity and reliability of fisheries control systems. Hybrid cloud edge infrastructures allow sensitive data to be processed onboard while synchronising with secure cloud servers when connectivity permits. Encryption, redundancy, and blockchain based traceability systems provide additional layers of protection against tampering and data loss. These technologies support the EU's requirement for secure, standardised, and interoperable data exchange between vessels, Member State control centres, the European Commission, and EFCA. Encryption, redundancy, and standardised APIs support secure, interoperable data exchange between vessels, control centres, the European Commission, and EFCA (Sylvester et al., 2021). As fisheries management becomes increasingly digital, the importance of robust cybersecurity measures cannot be overstated.

5. The Transition Fully Digital and Interoperable Fisheries

The transition to a human centred digital ocean requires balancing regulatory compliance with operational feasibility. Key challenges include the cost of equipment for small scale fisheries and traditional fishing, connectivity gaps in remote areas, cybersecurity risks, and the potential for data overload in control centres (Akpan et al., 2022). However, the benefits are substantial: improved stock assessment, reduced IUU fishing enhanced safety for crews, and better decision making for shipowners (Paiva et al., 2025). The evolution of new technologies opens opportunities to meet regulatory requirements while improving operational efficiency and sustainability.

In other words, the transition towards a fully digital and interoperable fisheries control system presents both opportunities and challenges. On one hand, the integration of VMS, AIS, VDES, REM, GNSS, AI based analytics, and secure data infrastructures offers unprecedented capabilities for monitoring fishing activity, improving compliance, and supporting sustainable resource management. These technologies enable higher resolution spatial and temporal data, automated detection of suspicious behaviour, and more accurate estimation of fishing effort. They also support ecosystem-based management approaches by providing detailed insights into fishing patterns, habitat interactions, and environmental conditions.

However, the implementation of these systems requires significant investment, particularly for small scale fisheries that may lack the financial capacity to adopt advanced onboard equipment. Connectivity gaps remain a challenge in remote ocean regions, although LEO satellite networks are rapidly reducing these limitations. Cybersecurity risks are also a growing concern, as increased digitalisation expands the attack surface for potential data breaches or manipulation. Ensuring the integrity of fisheries data is essential for maintaining trust among stakeholders and supporting evidence-based decision making.

Another challenge lies in the operational capacity of Member State control centres. The volume of data generated by high frequency VMS, REM, and sensor networks can be overwhelming without adequate automation and analytical tools. Risk based approaches, supported by AI driven anomaly detection, will be essential for prioritising inspections and focusing enforcement efforts where they are most needed. The success of Regulation 2025/2196 will depend on the ability of Member States to modernise their infrastructures, harmonise data standards, and collaborate effectively with EFCA and the European Commission.

Despite these challenges, the benefits of a human centred digital ocean are substantial. Enhanced transparency can reduce IUU fishing, improve stock assessments, and support more equitable access to marine resources. Fishers can benefit from safer operations, reduced administrative burdens through automated reporting, and improved market access through traceability systems. The convergence of regulatory reform and technological innovation provides a unique opportunity to strengthen the sustainability and resilience of European fisheries.

6. Conclusion

EU Regulation 2025/2196 represents a significant step toward a fully digital and integrated fisheries control system. Emerging technologies—including satellite communications, GNSS, AI, wireless sensor networks, and secure data infrastructures—will be central to enhancing compliance, sustainability, and operational efficiency. A human-centred digital ocean is achievable, provided that technological innovation is accompanied by adequate training, investment, and international cooperation.

Portugal began this journey in 1988 with a pioneering initiative to develop the Blue-Box system—the first VMS in the European Union (Portugal, 1988; Vítor, 1993; Vítor, 1997; Vítor, 1999; Vítor, 2000). The integration of GPS and Inmarsat-C into the Blue-Box represented a major technological breakthrough. The system has continued to evolve (Haugg et al., 2001) and remains commercially successful in several countries. Research and development teams, particularly at IST and ENIDH, have sustained the innovation trajectory of this pioneer and successful complete VMS system with a learning curve longer than 35 years. Recent technologies have been tested in our laboratories envisaging a new competitive system. With the emergence of new digital technologies, the present moment offers a unique opportunity to design the next-generation solution capable of meeting the increasingly demanding requirements of the fishing economy, aligned with market needs and EU regulations. Such a system can also deliver added value to stakeholders across the maritime domain, including the Navy, Coast Guard, Port Authorities, Marinas, Shipowners, and Research Institutes.

A human-centred digital ocean is within reach if technological progress is supported by robust governance frameworks, comprehensive training for fishers and authorities, and a commitment to interoperability and data integrity. As fisheries confront growing pressures from climate change, market dynamics, and ecological uncertainty, the modernisation of control systems will be essential to ensuring the long-term sustainability of marine resources and the resilience of the communities that depend on them.

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Intelligent Incipient Fault Detection in Two-Stroke Marine Diesel Engines using Residual Indicators

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Abstract: The digital transformation of maritime systems has increased the availability of operational data, creating new opportunities for human-centred decision support in ship operation and maritime education. Early fault detection in marine propulsion systems is essential to improve safety, reliability, energy efficiency and environmental performance, but it remains difficult in large two-stroke marine diesel engines because operating regimes are time-varying and measurements are affected by noise, outliers and operational/environmental disturbances. This paper presents a residual analysis-based methodology for incipient fault detection in a MAN B&W 6S60MC-C two-stroke main engine using operational time-series data generated in a Wärtsilä ERS TechSim engine-room simulator. Neural-network healthy baselines were trained from fault-free operating windows to predict nominal cylinder exhaust-gas temperature responses. Residuals between measured and predicted values were normalised per execution using median-MAD scaling, aggregated into fault-physics-consistent detection indices, and combined with temporal persistence logic to distinguish sustained degradation from short-lived transients. The methodology is assessed under representative degradation scenarios, including ramp-type faults and operating variability designed to emulate sea-state-induced disturbances. Results show earlier and more stable indication than direct thresholding of raw measurements, with confirmed detection in all reported S1 and S2 fault-insertion runs and no confirmed false alarms in the corresponding pre-fault healthy windows. The proposed workflow supports marine-engineer situational awareness, proactive maintenance planning and simulator-supported development of transferable onboard condition-monitoring workflows.

Keywords: condition monitoring; incipient fault detection; two-stroke marine diesel engines; residual analysis; exhaust gas temperature.

1. Introduction

Low-speed two-stroke marine diesel engines remain central to deep-sea propulsion, and their operating condition directly influences safety, fuel efficiency, thermal loading and maintenance planning. At the same time, the digitalisation of shipboard machinery systems has increased the availability of operational data, creating new opportunities for condition monitoring and decision support in marine engineering practice (Liang et al., 2024). This is relevant not only for machinery protection and maintenance planning, but also for human-centred decision support in simulator-based maritime engineering practice.

Early fault detection is difficult because measured variables evolve under changing load, propeller demand and environmental forcing, while measurement streams may include noise, spikes and short-lived transients. Direct thresholding of raw process variables is therefore often insufficient for incipient fault detection, because it does not reliably distinguish persistent abnormal deviation from normal context-driven variability (Jardine, Lin and Banjevic, 2006; Venkatasubramanian et al., 2003).

Cylinder exhaust gas temperature (EGT) is particularly relevant because it is standard marine-engine instrumentation and carries physically meaningful information about combustion balance, thermal loading and deviations in the air-fuel process. However, EGT abnormalities do not have a single spatial structure: some are distributed across the cylinder set, while others are primarily localised to one cylinder relative to the engine common mode.

This paper examines that distinction in a MAN B&W 6S60MC-C two-stroke main engine model implemented in a Wärtsilä ERS TechSim simulator. Two representative fault classes are considered: scavenge-air-side degradation and single-cylinder fuel-injector restriction. The contribution of the paper is to show that a

common baseline-residual-persistence backbone can be retained across both cases, provided that the final aggregation of residual evidence remains consistent with fault physics.

The remainder of the paper is organised as follows. Section 2 presents the experimental basis and the residual-generation framework. Section 3 defines the fault-physics-consistent detection indices for the two fault classes considered. Section 4 reports the main results for the S1 and S2 scenarios, together with a comparative interpretation. Section 5 discusses the main implications and limitations of the study. Finally, Section 6 summarises the conclusions and outlines directions for future work.

2. Experimental Basis and Residual-Generation Framework

The study used a Wärtsilä ERS TechSim engine-room simulator configured around a MAN B&W 6S60MC-C low-speed two-stroke main engine. The simulator allowed controlled and repeatable insertion of progressive abnormalities while preserving the multivariable and time-varying character of marine propulsion operation, which is valuable both for method development and simulator-supported maritime training (Wiig, Sellberg and Solberg, 2023).

The monitored domain was the cylinder EGT field. This domain was selected because EGT is standard shipboard instrumentation and because it can represent both fault classes examined in this paper: coherent multi-cylinder thermal response under scavenge-air-side degradation and persistent cylinder departure under localised injector restriction. The 12 baseline-model inputs were main-engine power, main-engine RPM, ship speed, main-engine fuel load, scavenge-air inlet pressure, scavenge-air manifold temperature, scavenge-air inlet temperature, charge-air-cooler inlet temperature, charge-air-cooler outlet temperature, turbocharger air-filter pressure drop, fuel-oil inlet temperature and main-engine fuel inlet pressure. The outputs were the six cylinder EGTs. The healthy reference set used for baseline development comprised ten healthy baseline executions covering calm, moderate and more severe wind/wave operating backgrounds, so that the nominal model was not calibrated only on a single ideal operating condition. The same healthy set was used only to establish nominal behaviour; fault-insertion executions were kept for detection assessment rather than for training.

2.1. Baseline modelling and residual processing

Healthy-window neural-network baseline models were used to estimate nominal EGT behaviour under normal conditions. The EGT baseline was implemented in MATLAB as a feedforward MLP regression network trained only with healthy data. It used the 12 inputs listed above, six cylinder-EGT outputs, one hidden layer with 10 neurons, Levenberg-Marquardt training (trainlm), a 70/15/15 train/validation/test split and 1 Hz data. The first 30s of each baseline file were excluded; non-finite samples were removed; missing values were linearly interpolated with nearest end-point completion; and model adequacy was checked using R^2 and $RMSE$ before residual generation. For each cylinder, the residual was defined as the difference between the measured EGT and the corresponding baseline prediction:

$$r_i(t) = y_i(t) - \hat{y}_i(t) \tag{1}$$

To improve comparability across runs, each residual series was normalised using statistics extracted from a healthy reference window. The normalised residual $z_i(t)$ was defined as

$$z_i(t) = \frac{r_i(t) - \tilde{r}_i}{1.4826\,\mathrm{MAD}(r_i)} \tag{2}$$

where $\tilde{r}_i$ is the median residual of cylinder i in the healthy reference window and $MAD(r_i)$ is the corresponding median absolute deviation. The factor 1.4826 is the standard consistency constant that renders the MAD asymptotically equivalent to the standard deviation under approximate normality. Its use here does not imply a normality assumption for the residuals; rather, it provides a statistically interpretable scale for cross-run and cross-cylinder comparison in the presence of skewness, outliers and short-lived measurement disturbances.

A smoothing stage was then applied before final alarm confirmation. Operationally, the residual-processing sequence was baseline prediction, residual computation, healthy-window median-MAD

normalisation, light temporal smoothing and persistence-based thresholding. Threshold exceedance was therefore interpreted together with temporal persistence so that short-lived fluctuations would not be treated as evidence of developing fault.

3. Fault-Physics-Consistent Detection Indices

In Scenario 1 (S1), the fault class considered is distributed degradation in the scavenge-air system of the main engine. Unlike a cylinder-specific malfunction, this type of deterioration affects the common air path serving the engine, namely the processes that govern scavenge-air delivery and charge-air conditioning. From a marine-engineering perspective, the consequence is not an isolated thermal imbalance in one unit, but a general deterioration in combustion-air supply, which is reflected in a coherent EGT shift across the cylinder set. The processed residuals were therefore aggregated into a global index defined as the root-mean-square across the cylinder set:

$$I_{\mathrm{RMS}}(t) = \sqrt{\frac{1}{N_c}\sum_{i=1}^{N_c} z_i^2(t)} \tag{3}$$

This index emphasises common growth of abnormality across cylinders and is therefore appropriate for shared-process disturbances such as turbocharger/turbine fouling and charge-air-cooler fouling. Here N_c denotes the number of cylinders; for the present engine, $N_c = 6$.

In Scenario 2 (S2), corresponding to single-cylinder fuel-injector restriction, the fault class is localised by construction. Here the useful signal is the persistent departure of one cylinder from the instantaneous engine common mode. The common-mode contribution was removed at each time step according to

$$\Delta z_i(t) = z_i(t) - \mathrm{median}_{\mathrm{k}}\{z_k(t)\} \tag{4}$$

and the differential detection index was then defined as follows, where $z_k(t)$denotes the normalised residual of cylinder k and N_c the number of cylinders considered:

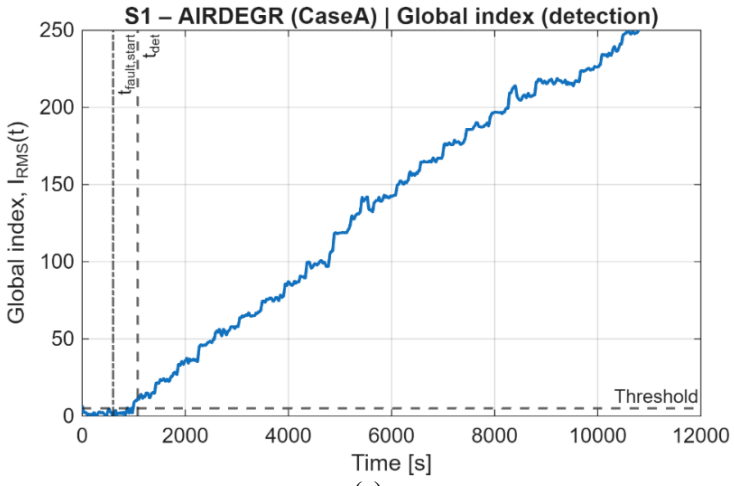
$$\mathrm{I_{diff}(t)} = \max_{\mathrm{i}}|\Delta \mathrm{z_i(t)}| \tag{5}$$

The key proposition is therefore simple: shared residual generation does not imply shared residual aggregation. A distributed degradation is better represented by a global aggregate index, whereas a localised cylinder fault is better represented by a differential inter-cylinder index. The experimental series used to test this proposition comprised two groups. The first examined scavenge-air-side degradation through two mechanisms: turbocharger/turbine fouling (Case A) and charge-air-cooler fouling (Case B). The second examined single-cylinder fuel-injector restriction. In both cases, faults were introduced progressively and evaluated under varying wind and wave conditions intended to emulate changes in the operating background associated with sea-state-related disturbance. Thresholds were derived from healthy-run index behaviour and combined with persistence logic; for S1 the global-index threshold $I_{(thr)}$ was estimated from healthy-run behaviour, whereas for S2 the decision threshold γ was estimated from the healthy-window distribution of $I_{(diff)}(t)$, with a minimum safeguard where required. For quantitative reporting, a confirmed detection was counted only when threshold exceedance satisfied the persistence rule after fault insertion; a false alarm was counted when the same confirmation logic was satisfied during the pre-fault healthy window.

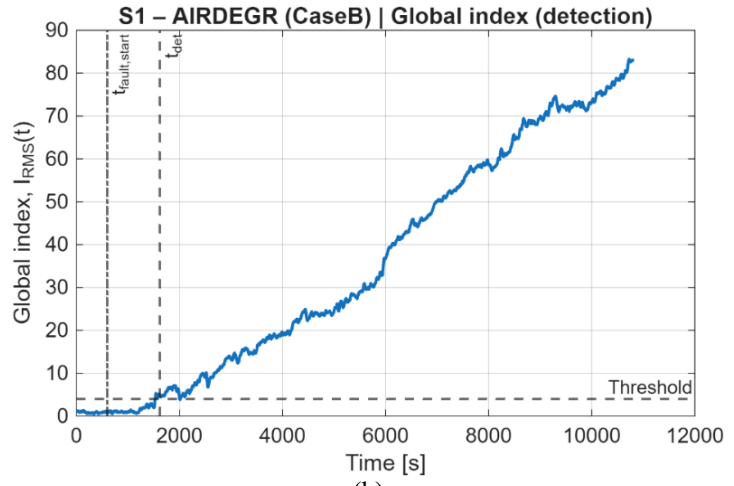
4. Results

4.1. Scavenge-air-side degradation (S1)

The S1 series produced the expected distributed thermal response across the cylinder set, and interpretation was therefore based primarily on the global index $I_{(RMS)}(t)$. As shown in Figures 1 and 2, the index remained close to its nominal band during healthy operation and then increased persistently after fault-ramp inception. Together with the coherent cross-cylinder rise of normalised residuals, this behaviour supports the use of a global aggregate indicator for distributed abnormality.



(a)



(b)

Figure 1. Global-index response for two representative scavenge-air-side degradation cases in S1: (a) turbocharger/turbine fouling (Case A) and (b) charge-air-cooler fouling (Case B). In both cases, the index remains low during the healthy interval and increases persistently after fault-ramp inception, supporting the use of a global aggregate indicator for distributed abnormality.

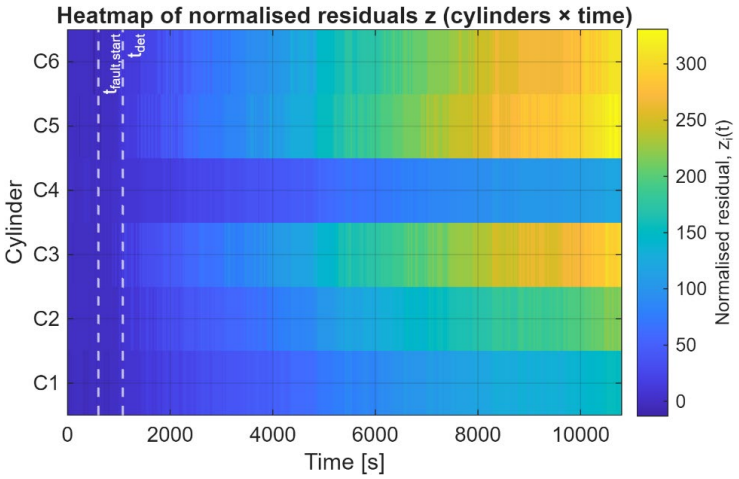


Figure 2. Representative heatmap of normalised residuals for the scavenge-air-side degradation series (Case A). The coherent increase across cylinders is consistent with a distributed thermal disturbance affecting the shared scavenge-air/combustion process rather than a localised cylinder fault.

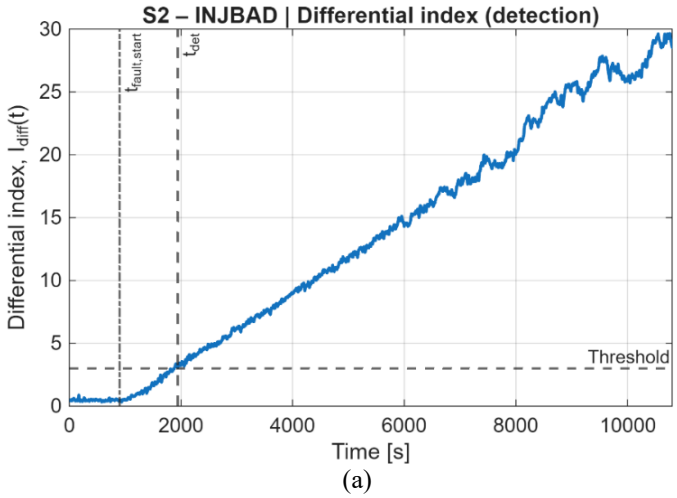
Table 1 summarises the full S1 results. Across both mechanisms, detection times fall within the same broad range, and the peak-to-threshold ratios $I_{(peak)}/I_{(thr)}$ indicate strong separation between nominal and degraded operation. Here H_s denotes significant wave height and Δt the detection delay from fault-ramp inception to confirmed detection. The ten tests were selected to span calm, moderate and more severe environmental conditions while keeping the imposed fault-ramp logic comparable across runs.

Table 1. Test conditions and detection results for the scavenge-air-side degradation series (S1), including turbocharger/turbine fouling and charge-air-cooler fouling cases under different environmental conditions.

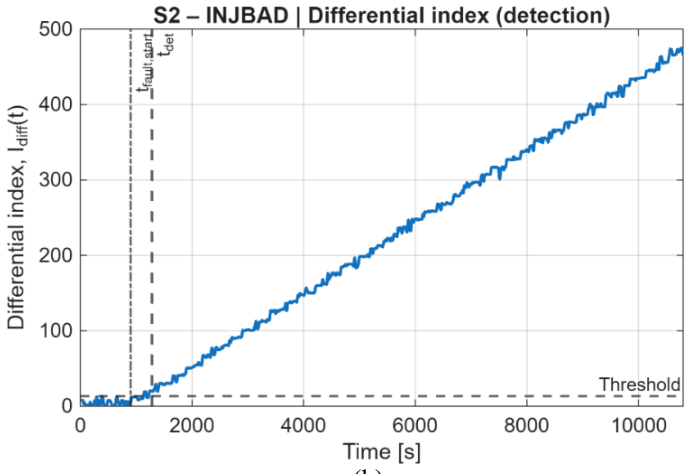
Test	Fault mechanism	Wind [m/s]	Direction [°]	Hs [m]	Δt [s]	Ipeak/Ithr
E1	Turbocharger/turbine fouling	10	0	2	229	43.05
E2	Turbocharger/turbine fouling	10	45	2	300	31.55
E3	Turbocharger/turbine fouling	15	90	4	221	34.19
E4	Turbocharger/turbine fouling	5	90	2	190	30.62
E5	Turbocharger/turbine fouling	0	0	0	211	37.66
E6	Charge-air-cooler fouling	8	120	5	169	38.17
E7	Charge-air-cooler fouling	8	0	2	200	35.40
E8	Charge-air-cooler fouling	6	90	4	230	36.24
E9	Charge-air-cooler fouling	8	45	2	247	36.60
E10	Charge-air-cooler fouling	4	0	4	235	35.90

4.2. Single-cylinder fuel-injector restriction (S2)

The S2 series posed a different diagnostic problem. Here the useful evidence was the persistent departure of one cylinder from the instantaneous engine common mode, and interpretation was therefore based on the differential index $I_{(diff)}(t)$ rather than the global index used in S1. This is physically consistent: a global aggregate is appropriate for distributed degradation, whereas a localised injector fault requires an inter-cylinder differential indicator if localisation is to be preserved. As shown in Figures 3 and 4, once common-mode behaviour was removed, the abnormal cylinder could still be tracked clearly under changing operating conditions.



(a)



(b)

Figure 3. Differential-index response for two representative single-cylinder injector-restriction cases in S2: (a) INJ1BAD and (b) INJ5BAD. In both cases, the index increases persistently after fault inception, supporting the use of a differential inter-cylinder indicator for localised abnormality.

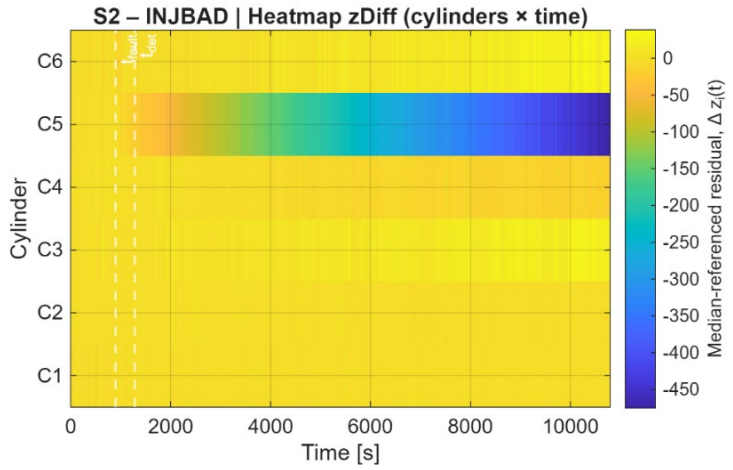


Figure 4. Representative heatmap of median-referenced inter-cylinder residual features for the injector-restriction series (S2). The persistent localised band identifies the affected cylinder, while the remaining cylinders remain close to the prevailing engine common mode.

Table 2 summarises the full S2 results. Across the series, the differential index provided confirmed detection in all cases while preserving localisation through identification of the dominant cylinder. Where an ERS alarm was recorded, residual-based detection preceded the simulator alarm by a substantial margin. In the table, $t_{(fault)}$ is the fault-onset time, $t_{(det)}$ the confirmed detection time, Δt the detection delay, γ the decision threshold, $I_{(peak)}/\gamma$ the peak-to-threshold ratio, $t_{(ERS)}$ the ERS alarm time and $\Delta t_{(ERS)}$ the lead relative to the simulator alarm.

Table 2. Detection results for the single-cylinder fuel-injector restriction series (S2), including affected cylinder, fault and detection times, decision threshold, peak-to-threshold ratio, and comparison with ERS alarm timing where available.

Test	Cyl.	t_{fault} [s]	t_{det} [s]	Δt [s]	γ	Ipeak/γ	ERS alarm	t_{ERS} [s]	Δt_{ERS} [s]
E1	4	600	890	290	3.00	34.34	No	–	–

Test	Cyl.	t_{fault} [s]	t_{det} [s]	Δt [s]	γ	Ipeak/γ	ERS alarm	t_{ERS} [s]	Δt_{ERS} [s]
E2	5	600	852	252	3.00	42.66	No	–	–
E3	5	600	910	310	3.00	29.94	No	–	–
E4	3	600	1355	755	3.00	17.42	No	–	–
E5	5	900	1283	383	13.13	36.16	Yes	10700	9417
E6	1	900	1942	1042	3.00	9.89	Yes	10750	8808

4.3. Comparative interpretation

Taken together, the two result sets support a single methodological conclusion. In both S1 and S2, the same baseline-residual-normalisation-persistence backbone was retained. What changed was the final aggregation of processed residual evidence: a global aggregate index for distributed degradation and a differential inter-cylinder index for localised abnormality. Compared with direct thresholding of raw EGT measurements, the residual-based formulation provides a more stable decision variable because it conditions the measured response against a nominal operating reference before persistence logic is applied. Performance was therefore assessed using detection delay, peak-to-threshold ratio, detection rate and confirmed false-alarm count in the corresponding pre-fault healthy windows. Confirmed detection was obtained in 10/10 S1 runs and 6/6 S2 runs, giving a 100% detection rate for the 16 reported fault-insertion trials. No confirmed false alarm was observed in the 16 paired pre-fault healthy windows under the same threshold-and-persistence logic.

This distinction is not merely mathematical. In S1, the abnormality manifests itself as a coherent thermal drift across the cylinder set, so the relevant evidence is the collective departure of the monitored domain from its nominal behaviour. Under such conditions, a global index is the appropriate representation because it preserves the distributed nature of the fault signature and avoids over-interpreting ordinary cylinder-to-cylinder variability. In S2, by contrast, the relevant evidence is the persistent deviation of one cylinder relative to the instantaneous engine common mode. In that case, a differential inter-cylinder formulation is required because a purely global metric would dilute the local signature and reduce localisation capability.

The comparative value of the two scenarios therefore lies in showing that methodological consistency does not require diagnostic uniformity. The same residual-generation framework can remain applicable across distinct fault classes, provided that the final decision variable is matched to the physical structure of the abnormality. In practical terms, this means that the residual layer may be common, while the final indicator must remain fault-physics-consistent if it is to support meaningful engineering interpretation. The combined results thus argue against a one-index-fits-all strategy and instead support a more disciplined approach in which residual evidence is aggregated according to how the fault manifests itself in the monitored domain.

5. Discussion

The study shows that residual-based monitoring provides a coherent framework for incipient fault detection in two-stroke marine diesel engines when the objective is to separate abnormal deviation from context-dependent nominal behaviour. The key methodological result is that the final detection index should preserve the physical structure of the fault evidence. This is also why the method is better suited to incipient detection than direct raw-variable thresholding under changing operating context. The quantified assessment supports this interpretation: all S1 and S2 fault-insertion runs were detected, and the pre-fault healthy windows did not generate confirmed alarms under the adopted persistence rule.

From an operational point of view, the distinction between distributed and localised abnormality directly influences how a warning should be interpreted. A distributed thermal shift points towards a shared subsystem problem, whereas a localised differential signature supports targeted attention to one cylinder and its injection hardware. The monitored domain used here, namely cylinder EGT, is realistic from a shipboard perspective because it relies on instrumentation commonly available in marine main engines. In that sense, the proposed indicators support situational awareness for marine engineers rather than algorithmic detection alone.

The study nevertheless has limitations. The data were generated in a high-fidelity simulator rather than collected onboard, and the paper focuses on a single monitored domain rather than full multi-domain diagnostic

fusion. The false-alarm assessment refers to the healthy baseline executions and paired pre-fault windows available in the simulator trials; it should therefore be interpreted as a controlled simulator result, not as a substitute for long-duration onboard false-alarm validation. Even so, the simulator-based approach remains a valuable intermediate step between conceptual diagnosis and onboard deployment.

6. Conclusions

This paper examined incipient fault detection in a two-stroke marine diesel engine using a residual-based framework built around healthy-window neural-network baseline modelling, residual computation, residual normalisation and temporal persistence. The EGT baseline was implemented as a feedforward MLP trained only on healthy simulator data, with 12 operating-context inputs and six cylinder-EGT outputs. Two representative fault classes were studied in a Wärtsilä ERS TechSim model of a MAN B&W 6S60MC-C main engine: scavenge-air-side degradation and single-cylinder fuel-injector restriction.

The results show that a common residual-generation backbone can be retained across different fault classes, provided that the final detection index is aligned with the physical manifestation of the abnormality. In the distributed degradation scenario, the informative evidence lies in the coherent departure of the cylinder set from its nominal thermal behaviour and is therefore more appropriately captured by a global aggregate index. In the localised injector-fault scenario, the informative evidence lies in the persistent separation of one cylinder from the instantaneous engine common mode and is therefore more appropriately captured by a differential inter-cylinder index.

Future work should extend the methodology towards onboard datasets, broader operating envelopes and additional monitored domains, while preserving the same emphasis on physical interpretability and operational usefulness. It should also address more explicit fault isolation and include additional fault classes beyond the two representative cases considered here. In that sense, the present study should be read as a focused contribution to incipient fault detection in marine propulsion systems and as a step towards more transferable condition-monitoring workflows for shipboard application.

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System-Theoretic Safety Assessment of Oil Discharge Monitoring Equipment (ODME) on Oil Tankers

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Abstract: Oil Discharge Monitoring Equipment (ODME) is a mandatory pollution-prevention barrier on oil tankers under MARPOL Annex I, yet non-compliant overboard discharges persist due to interactions between operators, software, sensors, actuators and operating conditions rather than isolated component failures. This paper develops an integrated safety-assessment framework combining the System-Theoretic Accident Model and Processes (STAMP) with Bayesian Network (BN) modelling for ODME operations. A hierarchical safety control structure is constructed; system-level hazards and unsafe control actions are identified across human, sensor, hardware, actuator, software and external categories; and the resulting causal map is converted into a BN populated with exponential failure models, expert elicitation and literature-based failure rates. Posterior inference yields a baseline non-compliant-discharge probability of 3.93×10^{-2}, and ratio-of-variation sensitivity analysis prioritises the dominant risk-influencing factors. Partial validation uses the three-axiom test. The framework gives practical guidance for crew training, alarm philosophy, control-logic design and risk-based maintenance, aligning with the IAMUC theme of human-centred digital oceans.

Keywords: STAMP; ODME; MARPOL Annex I; Maritime system safety; Tanker ship operations

1. Introduction

Under MARPOL Annex I, oily-mixture discharge from a tanker cargo area is permitted only en route, beyond 50 nautical miles from land, outside special areas, at an instantaneous rate not exceeding 30 L/nm and a total within 1/30,000 of the previous cargo (IMO, 2022). The Oil Discharge Monitoring Equipment (ODME) enforces these limits by integrating oil-content, flow, speed, GPS and valve-status signals and inhibiting discharge when any criterion is violated. In practice, the allowable total-discharge quantity is often calculated and entered manually by operators before discharge, introducing both unintentional calculation error and deliberate misreporting risk, particularly where tank-attribution assumptions (total previous cargo versus only the slop-originating tanks) are unclear. Despite automation, ODME-related compliance failures persist through interaction-based pathways - sensor drift, weak feedback loops, manual overrides, calibration errors and procedural omissions combining to defeat the interlock (Camliyurt et al., 2024).

Conventional event-chain methods under-represent interaction-driven hazards in socio-technical systems. The System-Theoretic Accident Model and Processes (STAMP) treats safety as a control problem and has been applied across maritime domains, including autonomous ships (Chaal et al., 2020) and tanker safety (Durukan et al., 2024), but remains qualitative and does not rank control flaws (Zhang et al., 2022). Bayesian Networks (BN) provide complementary probabilistic reasoning and have been combined with STAMP for tanker (Bulut Ceylan et al., 2025) and process-safety applications (Yousefi and Hernandez, 2020; Ahn, Kurt and Turan, 2022).

An integrated STAMP–BN treatment of ODME operations has not been reported. This paper closes that gap by: (i) defining an ODME safety control structure; (ii) identifying unsafe control actions (UCAs) and a coded hazard matrix; (iii) converting the STAMP output into a BN with exponential and expert-elicited priors; and (iv) ranking risk-influencing factors (RIFs) by ratio-of-variation with three-axiom validation. Section 2 presents the methodology, Section 3 the case application, and Section 4 closes with discussion and conclusions.

2. Methodology

2.1. ODME system definition

The system under analysis is the slop-tank overboard discharge function of a typical oil tanker. The boundary includes the operators (Master, Chief Officer, Officer of the Watch (OOW), pumpman, deck crew), the ODME control unit and its embedded software, the oil-content analyser, flow meter, GPS, ship-speed and valve-position feedback, the discharge pump and overboard valve, and the immediate operating environment. Five safety constraints govern the function: SC1 — discharge shall be inhibited when any MARPOL Annex I criterion is not met; SC2 — no control command shall execute without valid sensor measurements; SC3 — pre-discharge calibration, line flushing and zero-check shall be completed before the overboard valve opens; SC4 — manual overrides shall be deliberate, authorised, time-limited and logged; SC5 — the allowable total-discharge quantity (1/30,000 criterion) shall be correctly calculated, cross-checked and entered before discharge initiation.

2.2. STAMP analysis

controllers (human and automated) act on a controlled process through actuators and receive sensor feedback (Chaal et al., 2020). Accidents are treated as inadequate enforcement of safety constraints rather than isolated component failures. UCAs are classified into four categories (Chaal et al., 2020): a required action is not provided; an unsafe action is provided; an action is mistimed; or an action is applied too long or stopped too soon.

2.3. Bayesian Network model

Each UCA and supporting RIF is mapped to a node of a directed acyclic graph (DAG); arcs encode conditional dependence among technical, human, software and procedural factors. The top-event node is "ODME non-compliant discharge". All nodes are binary (Yes/No) in this initial model.

The joint probability of the network variables $U = A1, \dots, An$ is:

$$\mathrm{P(U)} = \prod_{\mathrm{i=1}}^{\mathrm{n}} \mathrm{P}\left(\mathrm{A_i} \mid \mathrm{Pa(A_i)}\right) \quad \textbf{(1)}$$

The marginal probability of node Ai is:

$$\mathrm{P(A_i)} = \sum_{\mathrm{U \setminus A_i}} \mathrm{P(U)} \quad \textbf{(2)}$$

Posterior inference, given evidence E, is computed as:

$$P(U \mid E) = \frac{P(U,E)}{\sum_U P(U,E)} \quad \textbf{(3)}$$

Prior probabilities of basic-event nodes are estimated from the exponential failure model:

$$P(X_{failure}) = 1 - e^{-\lambda t} \quad \textbf{(4)}$$

with $t = 1\ h$ and λ values from open technical sources. Conditional probability tables (CPTs) for intermediate nodes are populated by expert elicitation, calibrated against the open literature (Bulut Ceylan et al., 2025). Inference is performed in GeNIe (BayesFusion, 2024).

RIF influence is evaluated by the ratio of variation (RoV):

$$P(X_{failure}) = 1 - e^{-\lambda t} \quad \textbf{(5)}$$

where $\theta(Ai)$ and $\pi(Ai)$ are the prior and posterior of node Ai. Partial structural validation uses the three-axiom test : a parent change produces a consistent child change; proportional influences are consistent across parents; combined evidence is at least as strong as any subset.

3. Case application: ODME system on an oil tanker

3.1. ODME system description

The analysed configuration is a typical product/crude tanker fitted with a Type-approved ODME (e.g., Brannstrom OilCon Mark 6M). Slop-tank effluent is drawn through the sampling line to the oil-content analyser; flow and GPS feed the discharge-rate computation; the control unit compares rate, total quantity, position and special-area status against MARPOL limits and commands the overboard and recirculation valves. Special-area status is treated operationally as a geofenced, position-based condition derived from coordinates rather than

computed by the ODME, while the allowable total quantity (1/30,000 criterion) is a pre-discharge operator calculation and manual ODME entry subject to independent bridge/deck cross-check. The line-up, sampling loop and recirculation path are shown in Figure 1.

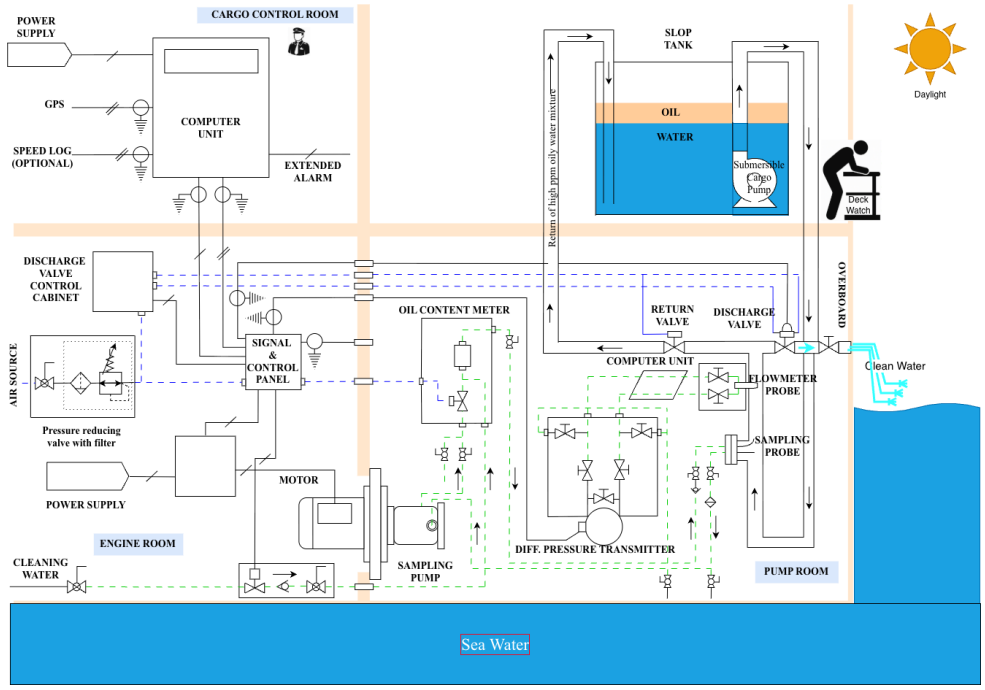


Figure 1. ODME slop-tank discharge operation: pump, sampling line, oil-content analyser, flow meter and overboard/recirculation valves.

3.2. Safety control structure

The ODME safety control structure (Figure 2) comprises five hierarchical layers: (a) regulator and class (IMO/Flag State, RO/Class, port-state control); (b) shipping company (DPA, technical superintendent, operations); (c) ship management (Master, Chief Officer); (d) operator and machine layer (pumpman, ODME control unit, sensors and actuators); and (e) the controlled process (slop-tank effluent and overboard line). Control flows downward and feedback (alarms, logs, surveys) flows upward.

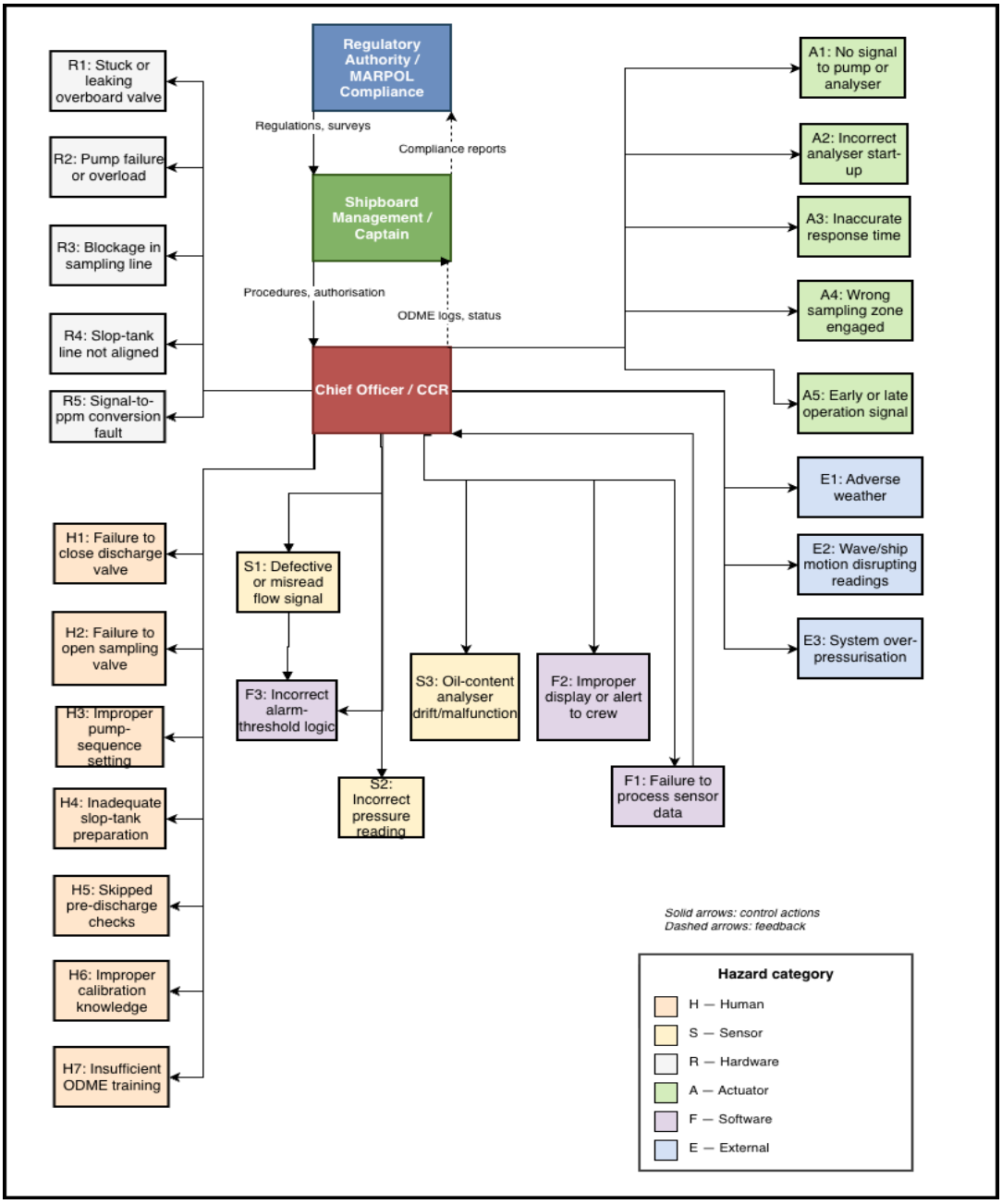


Figure 2. STAMP safety control structure for ODME operation on an oil tanker.

3.3. Hazard identification and UCA mapping

System components are coded as Human (H), Sensor (S), Hardware (R), Actuator (A), Software (F) and External (E), with sub-codes (e.g., H1–H7, S1–S4) capturing component-level hazards. Table 1 summarises the catalogue across operator errors, sensor drift, mechanical and conversion faults, control-signal anomalies, software-logic deficiencies and environmental disturbances. Table 2 maps the resulting unsafe control actions (UCAs) onto Leveson's four categories (not provided, provided unsafely, wrong timing, wrong duration).

Table 1. ODME hazard identification matrix.

Code	Category	Sub-component	Hazard description
H1–H7	Human	Ship crew	Operational, procedural, calibration and training-related crew errors

S1–S4	Sensor	Flow meter, pressure sensor, oil-content analyser, GPS/GNSS input	Signal defects, incorrect readings, sensor drift/malfunction, position-signal loss or offset
R1–R5	Hardware	Valve, pump, sampling/slop-tank lines, converter	Mechanical failure, blockage, mis-alignment, conversion fault
A1–A5	Actuator	Control panel	Missing, incorrect or mistimed control signals
F1–F3	Software	Control software	Data-processing, display and alarm-logic failures
E1–E3	External	Weather, wave motion, operational pressure	Environmental disturbances and over-pressurisation

Table 2. Representative ODME unsafe control actions (UCAs).

ID	UCA category	Unsafe control action	Linked hazards
U1	Not provided	Overboard valve close-command not issued when discharge rate exceeds 30 L/nm (15 ppm applies to clean-ballast discharge only, not to slop)	F3, A1, S3
U2	Provided unsafely	Discharge command issued inside special area or within 50 nm of nearest land	F1, F3, S4
U3	Wrong timing	Analyser start-up delayed; discharge begins before zero check completes	A2, A3, H5
U4	Wrong duration	Sampling-line flushing terminated too soon, leaving residual oil in line	A5, H3, R3
U5	Wrong duration	Manual override applied beyond the authorised, bridge-logged interval (e.g., calibration/troubleshooting)	H1, H6, F2

3.4. Bayesian Network construction and inference

The BN is derived from the STAMP output. Input nodes correspond to Table 1 codes and Table 2 UCAs; intermediate nodes group system-side (sensor, actuator, software, hardware) and non-system-side (human, procedural, external) failures; the top node T is non-compliant discharge. Technical priors come from Equation (4) with λ from class-society and OREDA-style sources; human and procedural priors are elicited from seven experts (master mariners and chief officers, mean experience 11.1 years, SD = 2.3 years); for conditional probability table (CPT) development each expert first gave independent estimates, which were reconciled in a moderated consensus round before agreed central values were encoded. Forward inference in GeNIe yields P(T = Yes) = 3.93×10^{-2}; reverse inference produces the posteriors and RoV in Table 3.

Table 3. Posterior probabilities and RoV ranking of dominant risk-influencing factors.

Rank	Code	Factor	Prior θ	Posterior π	RoV
1	H6/H7	Operator process-model mismatch (training, calibration knowledge)	0.041	0.293	6.15
2	S3	Oil-content analyser drift/malfunction	0.018	0.111	5.17
3	F3	Incorrect alarm-threshold logic	0.012	0.069	4.75

4	A1/A3	Discharge-command/valve actuation quality	0.022	0.115	4.23
5	H5	Skipped pre-discharge procedural checks	0.035	0.176	4.03

3.5. Model validation

Applying the three-axiom test: setting H7 (insufficient training) to 100 % raises the control-error intermediate from 0.039 to 0.853; adding H6 raises it to 0.964; adding H5 raises it to 1.000 for this normalised worst-case intermediate node. This bound follows from the CPT assumptions under simultaneous omission of all three checks and should be read as a model stress-test rather than an unconditional real-world certainty, since independent protective barriers may remain. Marginal influences are monotone and combined evidence exceeds any subset, providing partial structural validation. Empirical validation against port-state-control deficiency records is left for future work.

4. Discussion and Conclusions

The dominant risk-influencing factors are human–software interactions — training, calibration knowledge, alarm-threshold logic and procedural compliance — rather than hardware faults, consistent with recurring operational and procedural deficiency trends reported in port-state-control records (Paris MoU, 2024). Hardware-only reliability programmes yield diminishing returns; competency-based training and human–machine interface improvements offer larger marginal gains. The framework also captures non-linear risk amplification: when a technical deviation (e.g., S3 drift) and a procedural weakness (e.g., H5 skipped checks) co-occur, the top-event posterior rises faster than the sum of individual contributions — a pattern conventional event-chain methods cannot represent.

Practical implications from Table 3: (a) ODME-specific competency training drilling the full sequence (line-up → flushing → zero-check → discharge → log entry) through manufacturer-specific modules and simulator/replay drills to improve transferability across fleets and ODME types; (b) hardened procedural barriers (electronic checklists, two-person authorisation, inhibit-by-default logic); (c) revised alarm philosophy in which the analyser zero-fault is unmaskable; (d) risk-based maintenance focused on the analyser, overboard valve and signal-converter chain; and (e) mandatory independent cross-check of the manually entered 1/30,000 total-discharge limit. Limitations include binary-state simplification, expert-elicited priors and a generic tanker scope; future work will add multi-state CPTs and empirical calibration against deficiency data. Overall, the STAMP–BN framework yields a baseline non-compliant-discharge probability of 3.93×10^{-2} and identifies operator process-model mismatch, analyser integrity, alarm-threshold logic, valve-actuation quality and procedural compliance as dominant contributors aligning with the IAMUC vision of human-centred digital oceans.

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An Open-Source, Low-Cost Navigation Console for Maritime Education and Research

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Abstract: Maritime navigation simulators are widely used in training due to their ability to replicate realistic scenarios safely and cost-effectively. However, access to these systems is often limited by high demand and restricted training time. While commercial desktop, cloud, and virtual reality simulators, as well as some open-source solutions, provide alternatives, dedicated hardware consoles remain expensive and inflexible, limiting their accessibility and adaptability; particularly for emerging technologies such as wind-assisted propulsion systems. This paper presents the first version of a low-cost, open-access navigation console developed as part of the SOMOS project. The design prioritizes reproducibility, scalability, affordability, ease of assembly, and the use of widely available components. The proposed solution includes fully documented resources such as laser-cutting files, electronic schematics, software, and installation guidelines. The system is compatible with existing simulation platforms and designed with modularity in mind, enabling integration of additional features, including wind-assisted propulsion controls. This approach aims to expand access to practical training tools while supporting innovation in maritime industry.

Keywords: maritime simulator; control console; open-source; low-cost, training

1. Introduction

Maritime navigation simulators have become an essential tool of maritime education and training. They enable the realistic reproduction of a wide range of operational maritime scenarios at significantly lower cost and without the safety risks associated with onboard training. These simulators incorporate multiple vessel types, allowing mariners to train for diverse navigational contexts. They also make it possible to simulate emergency situations such as onboard fires, man-overboard events, or machinery failures. Due to their pedagogical value and the limited number of students who can use them simultaneously, simulator platforms are often heavily utilized. As a result, simulator training hours are typically constrained, and students frequently express the need for additional practice time.

To address this limitation, commercial desktop, cloud, and Virtual Reality based simulators are available (Tusher et al. 2024), along with open-source and free solutions such as Bridge Command (Bridge Command Project 2026). On the hardware side, dedicated commercial control consoles are designed to provide a more immersive maritime experience (Dahlstrom et al. 2009). However, their cost, often several hundred euros, generally restricts their use to maritime institutions. Moreover, these proprietary consoles offer limited flexibility for modification or integration with innovative systems. This is particularly relevant in the context of emerging technologies such as Wind-Assisted Ship Propulsion (WASP) systems, which are gaining increasing attention as part of the maritime sector's decarbonization efforts. A project proposes control consoles but with rare components and poor documentation (Bridge Command Controls 2026).

Within the SOMOS project (SOMOS Project 2026), we aim to develop innovative educational tools that integrate wind-assisted propulsion concepts into maritime training (Rieffel et al. 2025) such as a bridge simulator (SOMOS Simulator). This paper presents the first version of a navigation console developed as part of this initiative.

The main contributions of this work, in contrast to existing proprietary and semi-proprietary simulator control solutions, which are typically closed, costly, and difficult to adapt, the main contributions of this work are: (i) the design and implementation of an open, reproducible and low-cost maritime navigation console that explicitly addresses vendor lock-in and limited extensibility; (ii) a fully open-source hardware–software stack, including mechanical, electronic, and software components, enabling end-to-end replication without proprietary dependencies; and (iii) a modular research platform designed to support extensibility towards advanced control scenarios. The system is designed to be compatible with existing simulation software while remaining modular enough to integrate additional functionalities, such as WASP interfaces.

This paper details the technical design specifications process of the console and explains how it is used through SOMOS project. By providing an accessible, low-cost, and adaptable alternative to commercial solutions, this work contributes to expanding simulator-based training opportunities. The remainder of this paper is organised as follows: Section 2 reviews related work and defines design objectives; Section 3 presents the hardware and software implementation; Section 4 describes integration with bridge simulation systems; and Section 5 concludes the paper and outlines future work.

2. Related works and design objectives

This section reviews existing maritime simulation control solutions and identifies their main limitations in terms of cost, flexibility, and accessibility. It then defines the design objectives that guide the development of the proposed low-cost navigation console.

2.1. Existing solutions

Maritime simulators used for STCW training must comply with standards such as DNV-ST-0033 or RINA GUI34-ENG, requiring control interfaces that reflect real ship equipment. As a result, high-end simulators often rely on authentic bridge components. While this improves fidelity, it also introduces significant cost, maintenance complexity, and limited scalability. In practice, these systems are typically closed, vendor-dependent, and difficult to modify, which restricts their use in research and experimental development contexts.

For smaller installations, commercial solutions such as Ship Consoles developed by VRInsight (VR Insight Shop 2026) provide configurable control panels for different vessel types (e.g., single or dual propulsion systems, thrusters, azimuth systems). Although these products reduce entry cost (about 1000€) compared to full-scale simulators, they remain relatively expensive and are still embedded within proprietary ecosystems. This limits hardware-level access, prevents deep customisation, and makes integration with emerging research domains such as WASP challenging.

More fundamentally, existing solutions in both high-end and mid-range categories tend to prioritise operational realism over openness and extensibility. Documentation is often limited, hardware designs are not reproducible, and interfaces are not designed for modification. As a result, there is a clear gap between professional-grade simulators and low-cost, research-oriented or educational alternatives.

At the lowest end of the spectrum, simulators can be operated using standard input devices such as a mouse, keyboard, or joystick. While this approach maximises accessibility, it significantly reduces pedagogical value in bridge training contexts by removing spatial and functional correspondence with real ship controls.

Overall, current solutions reveal a trade-off between realism, cost, and openness, with very few systems addressing all three simultaneously.

Arduino-based systems and open-source microcontroller platforms have been extensively used in engineering education, research, and tangible interface design, particularly for prototyping interactive systems and adapted low-cost human–computer interfaces (Pearce 2012; Gershenfeld 2005). Situational awareness visualization approaches have also been explored in cyber-physical monitoring contexts (Brosset et al., 2017), which are relevant for operator interface design in maritime control systems. These approaches demonstrate the effectiveness of physical interfaces in supporting experiential learning and rapid prototyping. However, their application to maritime bridge simulation remains limited, and existing implementations rarely address the requirements of reproducibility, modularity, and compatibility with professional-grade simulation environments.

2.2. Design objectives

The main objective of this work is to provide to maritime students and professionals open access, low-cost, adaptable control interfaces for simulation environments. The design objectives are:

- Open and free reproducibility,
- Adaptability and scalability,
- Low cost,
- Ease of assembly and implementation,
- Reliance on widely available, standard components.

A further objective is to support student-led experimentation and iterative development, enabling active learning and rapid prototyping. The system is designed to remain functional in resource-constrained environments without requiring specialised infrastructure.

Overall, the literature highlights a mature landscape of maritime simulation environments in which significant advances have been achieved in visual fidelity, system integration, and training effectiveness. However, most developments remain concentrated on software-level simulation platforms and proprietary hardware ecosystems. As a result, there is still limited work addressing open, low-cost, and modular physical control interfaces that can be freely reproduced, modified, and extended for research and educational purposes. This gap is particularly relevant for emerging applications such as WASP, which require adaptable and extensible control architectures beyond traditional bridge configurations.

3. Console Design and implementation

A reference implementation of the console is presented, along with detailed design steps to enable replication and adaptation. The system is based on the Arduino platform due to its accessibility, extensive documentation, and large user community.

Development follows an open collaborative approach, with all resources hosted in a public repository supporting community contributions: https://github.com/ENSM-Nantes/ShipController. The reference developed console is shown in Figure 1. It is intended as a baseline design rather than a final product.

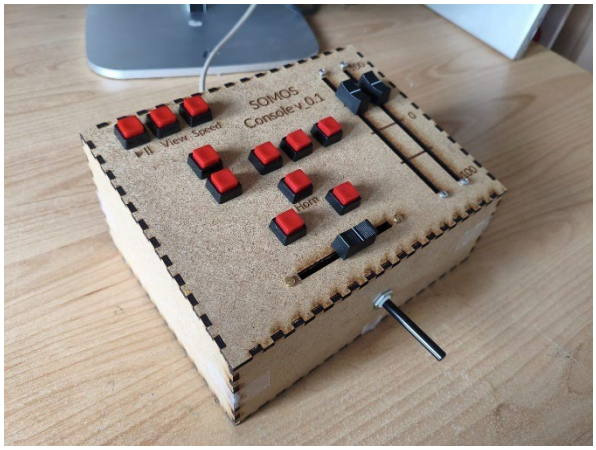


Figure 1. Ship Controller before installing the wheel.

3.1. Hardware

The console is based on an Arduino Leonardo microcontroller connected to a set of input devices. The configuration can be adapted depending on the target application. The reference configuration includes:

- 3 push buttons for simulator control (play/pause, camera view, simulation speed)
- 8 push buttons for ship functions (e.g., horn, on/off Fletner rotors)

- 2 sliding potentiometers for engine power control
- 1 rotary potentiometer for rudder control

Wiring details and assembly instructions are fully documented in the public repository in order to facilitate replication by users without specialised knowledge in electronics. The electrical connections are intentionally kept simple: push buttons are connected to digital inputs, while potentiometers are connected to analog inputs of the Arduino Leonardo. Particular attention was given to accessibility and ease of implementation, as the system is primarily intended for maritime students, instructors, and professionals rather than electronics specialists. Step-by-step guidance, wiring schematics, and configuration examples are therefore provided to minimise technical barriers and support straightforward assembly, maintenance, and adaptation of the console.

All the system can be packed in an adapted box. For this, we decided to use a Laser cutting machine because it has become affordable technology for small FabLab's. For creating the schematics, we used Boxes.py (Boxes.py 2026) tool selecting Console option. Boxes.py is a an open-source project that generates laser cutting designs for building boxes. Afterwards, we added the necessary number of holes for the desired controllers and engraved marks. The result is presented in Figure 2. All designs are available in the Git repository. The files are editable for making corrections or adaptations.

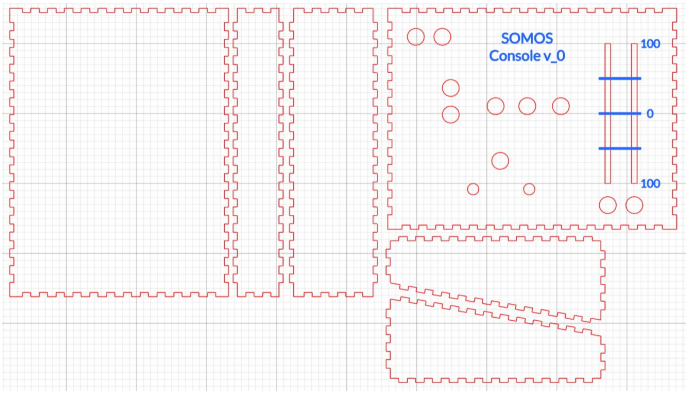


Figure 2. Laser-cutting design files for constructing the console enclosure.

Nowadays, numerous projects propose laser cutting and 3D printing files. Nevertheless, in low-cost applications, the solution to use a free box or Tupperware with adapted holes must not be ignored.

3.2. Software

The console emulates a standard Human Interface Device (HID) joystick, ensuring native compatibility with major operating systems such as Windows and Linux without requiring proprietary drivers. The software implementation is based on the Arduino Joystick Library (Arduino Joystick Library 2026), which enables the Arduino Leonardo microcontroller to expose analog and digital inputs directly as joystick axes and buttons recognized by simulation environments.

The software architecture was intentionally designed to remain simple, modular, and easily modifiable in order to facilitate adaptation by users without advanced expertise in embedded systems or software engineering. Input acquisition is performed through periodic polling of analog and digital signals connected to the potentiometers and push buttons. Analog values are mapped to configurable ranges corresponding to simulator control parameters, while digital inputs are processed with basic debouncing mechanisms to ensure stable operation and avoid unintended activations.

To maximise interoperability, the system does not depend on a specific maritime simulator and can therefore be integrated with any software capable of receiving joystick or generic HID inputs. This approach allows the console to interface not only with the SOMOS bridge simulator but also with commercial simulators (cloning the same inputs mapping), open-source navigation environments, and experimental research platforms. The provided code can be uploaded directly to the Arduino Leonardo using the Arduino IDE, which simplifies deployment and maintenance across different educational and research contexts.

The open-source nature of the software further supports extensibility and experimentation. Users can modify input mappings, add new controls, or implement alternative interaction logics according to their operational or pedagogical requirements.

3.3. Cost

The total cost depends on the selected components, particularly whether original or clone parts are used. Table 1 summarises indicative prices based on prices on a local store selling original components and on-line store with clone components.

Table 1. Indicative prices of materials.

Component	Quantity	Original components (€)	Clones (€)
Wood	1	4	0
Arduino Leonardo	1	27	4.70
Wires	1 kit	4.95	0.50
Boutons	11	0.70	0.20
Rotary potentiometer	1	1.90	1.50
Slide potentiometers	2	9.90	1.50
TOTAL		**65.35**	**11.9**

Results show that the system can be built for between €11.90 and €65.35. Performance differences are minimal for most components, although sliding potentiometers may affect control smoothness. Overall, the proposed design achieves a substantial cost reduction compared to commercial alternatives while maintaining functional adequacy.

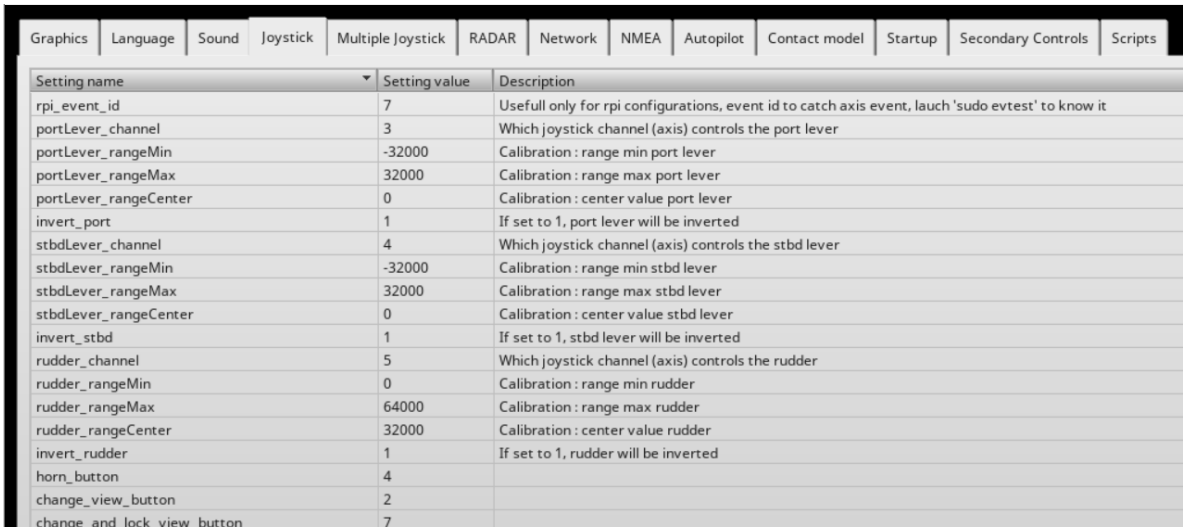
4. Integration with bridge simulators

The console has been validated using the bridge navigation simulator developed within the SOMOS project at the French Maritime Academy (ENSM) (Github SOMOS Simulator 2026). Figure 3 illustrates a simple installation created for testing purposes. The objective is to support control interfaces for WASP systems, including sails, Fletner rotors, and kite-based propulsion. In this manner, the simulator can be used independently with the console without requiring other peripherals. This configuration facilitates testing and demonstrations.



Figure 3. Console with open-source simulator controlling Fletner rotors.

For adapting its functioning to our particular needs, a configuration interface (Figure 4) enables mapping all inputs to simulator inputs and calibrating using minimum, maximum, and centre values. Each button and potentiometer is identified by a number. Generic testing tools such as joy.cpl (by default in windows) or evtest for Linux allow identifying them easily without needing to be interested in Arduino's code.



Setting name	Setting value	Description
rpi_event_id	7	Usefull only for rpi configurations, event id to catch axis event, lauch 'sudo evtest' to know it
portLever_channel	3	Which joystick channel (axis) controls the port lever
portLever_rangeMin	-32000	Calibration : range min port lever
portLever_rangeMax	32000	Calibration : range max port lever
portLever_rangeCenter	0	Calibration : center value port lever
invert_port	1	If set to 1, port lever will be inverted
stbdLever_channel	4	Which joystick channel (axis) controls the stbd lever
stbdLever_rangeMin	-32000	Calibration : range min stbd lever
stbdLever_rangeMax	32000	Calibration : range max stbd lever
stbdLever_rangeCenter	0	Calibration : center value stbd lever
invert_stbd	1	If set to 1, stbd lever will be inverted
rudder_channel	5	Which joystick channel (axis) controls the rudder
rudder_rangeMin	0	Calibration : range min rudder
rudder_rangeMax	64000	Calibration : range max rudder
rudder_rangeCenter	32000	Calibration : center value rudder
invert_rudder	1	If set to 1, rudder will be inverted
horn_button	4	
change_view_button	2	
change_and_lock_view_button	7	

Figure 4. Console configuration interface.

Potentiometer calibration is performed using standardised ranges depending on the simulation environment (by default, 32.000, 32.000 and 0, respectively). These values can be also identified thanks to the testing tools.

In combination with open-source simulation software such as the developed bridge simulator, the proposed console constitutes a flexible experimental platform for exploring new functionalities and investigating ergonomic aspects of maritime human–machine interaction. Its modular and open architecture enables rapid prototyping and evaluation of alternative control layouts, interaction methods, and operator feedback mechanisms, while facilitating the integration of emerging technologies such as WASP systems. This approach supports both training applications and research activities related to usability, interface design, and operational efficiency in maritime simulation environments.

5. Perspectives and Conclusions

This paper presented a low-cost, open-source navigation console designed to improve accessibility to maritime simulation training. By leveraging widely available components and an Arduino-based architecture, the proposed system significantly reduces cost barriers while maintaining functional relevance for training applications. The main contribution is a fully reproducible and modular hardware–software platform that can be extended for advanced maritime applications.

Future work will focus on improving and expanding documentation, providing application-specific examples, and presenting integration with advanced propulsion and control systems, particularly with WASP control systems. In parallel, user studies involving maritime students will be conducted to quantitatively and qualitatively evaluate the proposed system, including usability, reproductivity of the system, and perceived realism, in order to validate its effectiveness as a training interface. Community contributions through the open repository are encouraged to support continuous development and validation in educational and research contexts.

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Ship Safety Domains: Concept Development Review

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Abstract: The Ship Safety Domain (SSD) is one of the most important concepts in research on safety of navigation, navigational risk assessment, and the design of decision-support and collision avoidance systems for both conventional and autonomous ships. An SSD is defined as the area surrounding a vessel that should remain clear of other objects to ensure safe navigation, considering ship characteristics, environmental conditions, and operational constraints. Despite its extensive use in research and applications, there is no universally accepted definition or standardized modeling approach for SSDs. This paper provides a concise review of the current state of research on SSDs. It brings an overview of the concept, and it examines commonly used definitions and the conceptual foundations of SSDs, highlighting model development throughout history and corresponding interpretations and scope across the literature. A general categorization of SSDs is then presented, including static and dynamic domains, deterministic and probabilistic models, as well as geometric, behavioral, and data-driven approaches. The study is based on 12 scientific articles and key studies focusing on modeling assumptions, input parameters, and validation methods. Factors influencing domain size and shape, such as vessel dimensions, maneuverability, speed, traffic density, human factors, and environmental conditions, are discussed. The paper synthesizes the reviewed work to identify prevailing methodologies, limitations, and open challenges, particularly regarding model standardization. The findings provide a structured overview of SSD research and outline directions for future development in maritime safety studies.

Keywords: ship safety domain; maritime safety; navigational risk assessment; collision avoidance; maritime autonomous surface ships

1. Introduction

Maritime transportation, in terms of volume carried, forms the most important branch of global trade, carrying an estimated 80% of the world's goods by volume (UNCTAD, 2023). This fact alone indicates that it is of global importance to prioritize the safety of navigation for the global merchant fleet. Collisions at sea remain a constant and expensive hazard. According to the European Maritime Safety Agency (EMSA), collisions accounted for more than 30% of all recorded maritime casualties in the last decade, resulting in loss of life, cargo, and significant environmental damage (EMSA, 2023). Despite decades of regulatory development, most notably the International Regulations for Preventing Collisions at Sea (COLREGs, 1972), the prevention of ship-to-ship and ship-to-obstacle collisions continues to demand better analytical tools, more rigorous risk criteria, and a deeper understanding of the spatial behavior of vessels' movements.

One of the most appropriate analytical concepts developed to address this challenge is the concept of the ship safety domain (SSD). First established in the context of maritime traffic engineering by Fujii and Tanaka (1971) and subsequently formalised by Goodwin (1975), the ship domain is broadly understood as the region of water surrounding a vessel that the navigator (in this sense, Officer of the Watch or Master) wishes to keep free of other ships and obstacles. This concept is still in a conceptual and scientifically emerging phase of research. Over the past five decades, the concept has been elaborated into a diverse family of models, from statistical, analytical, knowledge-based, fuzzy, probabilistic, and increasingly AI-driven, each reflecting the navigational assumptions, data sources, and computational tools of its era.

The rapid expansion of the use of Automatic Identification System (AIS) data since the mid-2000s has fundamentally transformed how ship domains are empirically determined, enabling researchers to move from small-sample simulator studies and traffic surveys to analyses of hundreds of thousands of real ship encounters

(Hansen et al., 2013; Hörteborn et al., 2019). Additionally, the emergence of Maritime Autonomous Surface Ships (MASS) has created an urgent need to revisit domain models that were originally conceived around a human navigator's intuition and decision-making. As autonomy levels increase, domain theory must evolve to follow collision avoidance algorithms, regulatory compliance frameworks, and risk assessment tools in an environment where "good seamanship" can no longer be assumed to reside in a human on the bridge (Szlapczynski and Szlapczynska, 2017; Li et al., 2025)

This paper aims to present the chronological development of ship safety domain models from their origins to contemporary formulations. It also aims to synthesize the general application areas of SSD in scientific research and, lastly, to identify the key conceptual directions and open research challenges that define the current state of the field. The remainder of the paper is structured as follows. Section 2 establishes general definitions and the concept of SSDs. Section 3 presents a chronological review of model development across four periods: the founding era of the 1970s, the conceptual expansion of the 1980s and 1990s, the analytical and data-driven advances of the 2000s and 2010s, and the dynamic and MASS-oriented models of the 2020s. Section 4 surveys the application domains of SSD theory. Section 5 discusses themes, contradictions, and directions for future research, and Section 6 presents conclusions.

2. Concept and General Definitions

The SSD is most easily understood as an area of water surrounding a vessel that the navigator wishes, or is functionally required, to keep clear of other ships and fixed or floating obstacles. It is a spatially defined safety buffer representing a translation of the navigator's intuitive sense of "enough room" into a geometric construct for analysis, simulation, and algorithmic implementation. This concept draws a direct parallel with the term "personal space" from social psychology: just as individuals maintain a comfort zone in crowded environments, navigators maintain an operational buffer whose size and shape depend on context, speed, vessel characteristics, and individual experience (Zhao, Wu and Wang, 1993)

Goodwin's definition (1975) remains the most widely cited: the ship domain is "the effective area around a ship which a navigator would like to keep free with respect to other ships and stationary objects." This formulation is deliberately broad. It makes no prescription about shape, size, or how the boundaries are determined. It does, however, capture the essential character of the concept: the domain is:

- Subjective (reflecting what a navigator would like),
- Spatial (occupying a defined area around the vessel),
- Protective (defining a zone that should remain free of hazards).

These three features together distinguish the SSD from simpler safety metrics such as the closest point of approach (CPA) or the distance at the closest point of approach (DCPA), which are scalar.

For easier understanding, domain geometries can be grouped into four categories:

- Circular and elliptical domains: the simplest models, computationally convenient but limited in their capacity to represent directional asymmetry,
- Sector-based and polygonal domains: models that approximate asymmetry by assigning different radii to different bearing sectors,
- Fuzzy and probabilistic domains: models where the boundary is a graduated zone expressed as a membership or density function, easy to integrate with quantitative risk frameworks.
- Dynamic domains: models whose shape and size change in real time as a function of vessel speed, heading, manoeuvring capacity, or environmental conditions. These represent the current frontier and are particularly relevant to MASS.

2.1. Effective Domain vs. Declarative Domain

A fundamental difference in the concept of SSD research is between the effective domain and the declarative domain, first systematically explored by Pietrzykowski and Uriasz (2009). The effective domain is the area a navigator actually maintains. An empirical quantity derivable from AIS data or radar. The declarative domain is the area navigators state they would maintain under ideal conditions. A normative quantity extracted through questionnaires or simulator studies. Wielgosz and Pietrzykowski (2022) demonstrated that the effective domain is systematically smaller than the declarative domain, and formulated a universal coefficient describing

this relationship across encounter situations, ship sizes, and speeds. A domain calibrated on declarative data will be more conservative than one derived from AIS observations, and neither is correct in an absolute sense, as they address different analytical questions.

2.2. Safety Criteria and Domain Limits/boundaries

The domain's safety criterion defines the condition under which the presence of another vessel within the domain signals a threat requiring action. Early models applied binary criteria, which turned out to be scientifically incorrect over time. Zhao, Wu and Wang (1993) addressed this by introducing fuzzy boundaries, where membership transitions continuously from "safe" to "dangerous" across a zone. This formulation proved highly influential and resulted in a decent number of fuzzy and probabilistic models that more faithfully represent navigational uncertainty.

The shape of the boundary itself has also been one of the main questions regarding the concept. The earliest statistical models produced elliptical or circular forms (Fujii and Tanaka, 1971), or asymmetric sector-circle composites (Goodwin, 1975), reflecting the directional asymmetry of navigational danger. Later analytical models produced polygonal, quaternion, and fully dynamic boundaries that vary continuously with speed, heading, manoeuvring characteristics, and environmental conditions. As Szlapczynski and Szlapczynska (2017) observed, this presence of different shapes has consequences in collision avoidance decisions, near-miss detection thresholds, waterway capacity estimations, and maritime traffic complexity evaluations. For better visualization of the idea behind the main parameters of SSDs, there is a sketch in Figure 1 below.

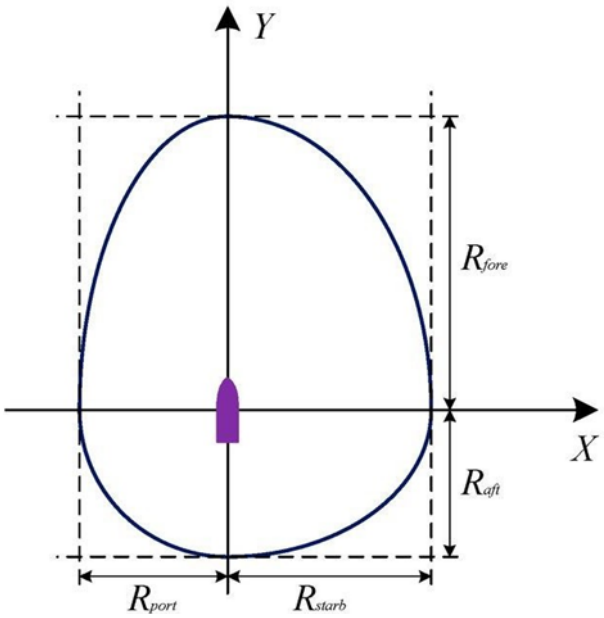


Figure 1. The diagram of the Quaternion ship domain (Wang et al., 2009).

3. Development of Ship Safety Domain Models

The history of SSD research spans more than five decades and can be divided into four periods, each characterised by a dominant methodological paradigm. The following subsections present this development, placing every model into its era within its context and noting the incremental conceptual advances that link successive phases.

3.1. The Founding Era and Early Work

The ship domain concept emerged from applied research on maritime traffic engineering in Japan. Fujii and Tanaka (1971) were investigating the capacity of navigation channels when they observed that each vessel effectively occupies a larger operational area than its physical dimensions. They termed this the effective domain and modelled it as an ellipse with a semi-major axis of approximately four ship lengths ahead, two astern, and about 1.6 lengths to each beam. The primary motivation was functional. Knowing the effective

domain, the saturation capacity of a waterway can be calculated. The domain was then more of a traffic engineering instrument rather than a safety concept.

Goodwin (1975) shifted the focus toward collision avoidance and safety. Drawing on radar simulator exercises and systematic traffic surveys in the southern North Sea, they constructed a domain model comprising three circular sectors of different radii, reflecting the asymmetric character of navigational danger. The ahead sector carries the largest radius, the starboard sector an intermediate one, and the port-and-astern sector the smallest. This asymmetry was grounded in the structure of the COLREGs, which assign different responsibilities depending on the relative bearing of an approaching vessel. Goodwin's model thus embedded regulatory logic directly into the geometric form of the domain, a feature that has remained influential in knowledge-based domain design ever since.

Coldwell (1983) extended domain analysis to restricted and confined waterways, revealing that ship size brings a significant influence on domain shape, with larger vessels requiring proportionally greater lateral clearances. This recognition that a single universal domain model cannot adequately describe navigation across all water area types became a recurring theme in subsequent research.

3.2. Conceptual Expansion in the 1980s and 1990s

Davis et al. (1980) introduced an important conceptual companion to the domain: the arena. While the domain defines the space a navigator wishes to protect, the arena represents a larger concentric region defined as the space within which monitoring and action begin. This two-tier structure provided a richer framework for simulating multi-ship collision avoidance and has been revived in recent work on autonomous systems (Szlapczynski and Szlapczynska, 2021).

The most significant conceptual advance of the 1990s came from Zhao et al. (1993), who brought social psychology to bear on the domain problem. Using proxemics theory, they argued that ship domain behaviour is a manifestation of spatial self-regulation, and introduced fuzzy set theory to model the domain boundary as a graduated zone characterised by a membership function transitioning from zero to maximum risk. This formulation addressed a genuine weakness of earlier binary models and opened the door to systematic integration with fuzzy collision risk indices.

3.3. Analytical and Data-Driven Models in the 2000s and 2010s

At the beginning of the 21st century, domain research became substantially more analytical. Pietrzykowski and Uriasz (2009) provided a complete methodological taxonomy of domain determination approaches. Statistical, analytical, and artificial intelligence contributed a fuzzy neural domain model for open sea navigation that exemplified the AI branch, using a self-learning neural network to capture the complex relationship between domain size and vessel-specific and environmental factors.

Wang et al. (2009) proposed the quaternion ship domain, a unified analytical framework in which the boundary is expressed as a single equation parameterised by four independently variable radii (forward, aft, starboard, port). A Quaternion is arguably one of the most comprehensive SSDs even today. Within the Quaternion SSD, elliptical and sector-based models are all recoverable as special cases. This generality made it one of the most widely adopted frameworks for collision avoidance research, particularly for autonomous navigation applications.

The adoption of AIS technology introduced a transformative data resource. Hansen et al. (2013) were among the first to derive domain dimensions systematically from large-scale AIS records, analysing vessel encounters in the Great Belt strait and defining a "comfort ellipse" consistent with the elliptical form proposed by Fujii and Tanaka, though with somewhat different proportions. Their finding that domain size appeared to be independent of ship length contrasted with earlier simulator-based results and foreshadowed the ongoing debate about what AIS-based domain studies actually measure.

Szlapczynski and Szlapczynska (2021) contributed the first comprehensive critical review of contemporary domain models, identifying persistent ambiguities in boundary definition and safety criteria, and beginning to map the expanding application landscape of domain theory. Hörteborn et al. (2019) extended this empirical research to approximately 600,000 ship encounters at 36 locations worldwide, confirming the elliptical form with a consistent forward-and-starboard offset, and finding no statistically significant relationship between ship length and domain dimensions in their global dataset.

3.4. Dynamic, Probabilistic, and MASS-Era Models

The early 2020s have seen domain research advance on two fronts simultaneously. Pietrzykowski and Wielgosz (2021) used an ECDIS-equipped navigation simulator with experienced deck officers to determine effective domains for vessels of different sizes and speeds, applying genetic algorithms to fit elliptical approximations and deriving explicit mathematical relationships between ship length, speed, and domain dimensions for cargo and passenger vessel categories. Wielgosz and Pietrzykowski (2022) extended this work to establish a universal relationship between declarative and effective domains.

On the system design side, Szlapczynski and Szlapczynska (2021) developed a domain-based collision risk model specifically engineered for near-miss detection and collision alert systems, introducing auxiliary temporal parameters, which are time of domain violation, time of domain exit, and vessel proximity relative to the domain boundary.

The most recent comprehensive synthesis (Li et al., 2025) analysed 241 domain-related publications through November 2024 and identified the MASS challenge as the defining problem for the next phase of domain research, noting that most existing models are conditioned on human navigational behaviour and cannot be directly transferred to autonomous decision-making contexts. Key open challenges include the absence of internationally agreed domain-based safety standards for MASS, the difficulty of encoding COLREGs-compliant behaviour in domain-based algorithms, and the need for real-time adaptive domains responsive to dynamic environmental and traffic conditions.

Table 1 below shows a summary of the most important and widely known SSDs today. It can easily be concluded that most SSD through history were elliptically shaped, determined by statistical observations. This changed gradually to variable shapes determined by tools such as AIS, ECDIS, and simulations.

Table 1. Summary of representative ship safety domain models: shape, methodology, and primary application.

Author(s)	Year	Domain Shape	Methodology	Primary Application
Fujii & Tanaka	1971	Ellipse	Statistical	Waterway capacity
Goodwin	1975	Sector (3 sectors)	Statistical	Traffic engineering
Davis et al.	1980	Ellipse + arena	Analytical	Multi-ship simulation
Coldwell	1983	Asymmetric ellipse	Statistical	Restricted waters
Zhao et al.	1993	Fuzzy polygon	Knowledge-based	Collision avoidance
Pietrzykowski & Uriasz	2009	Variable/neural	AI/analytical	Open sea safety
Wang et al.	2009	Quaternion	Analytical	Collision avoidance
Hansen et al.	2013	Ellipse	Empirical (AIS)	Capacity analysis
Horteborn et al.	2019	Ellipse	Empirical (AIS)	Domain redefinition
Pietrzykowski & Wielgosz	2021	Ellipse	Simulation (ECDIS)	Size & speed impact
Szlapczynski & Szlapczynska	2021	Variable	Analytical	Near-miss
Wielgosz & Pietrzykowski	2022	Variable	Survey + simulation	Declarative vs. effective

4. Applications of Ship Safety Domains

The idea of SSD has evolved from a narrow traffic-engineering instrument into a comprehensive framework serving several distinct application areas in the maritime safety domain. This section surveys the principal areas, showing how each area has developed in parallel with the modelling advances described in Section 3.

4.1. Waterway Capacity and Traffic Engineering

The original motivation for the concept of SSD was the estimation of waterway capacity. Fujii and Tanaka (1971) recognised that the throughput of a navigation channel is constrained not by vessel dimensions but by the effective area each vessel claims during transit. By quantifying this effective domain, the maximum sustainable traffic density can be calculated. This application has kept its practical importance as port traffic has intensified globally. More recent work has extended the approach to complex port geometries, channel intersections, and traffic separation schemes (TSS) using AIS-derived domain estimates as calibration inputs (Hansen et al., 2013; Hörteborn et al., 2019).

4.2. Collision Avoidance

Collision avoidance is the application area most closely identified with SSD research. The fundamental logic is that an encounter between two vessels is safe as long as neither vessel's domain is interfered with by the other; a domain violation triggers an evasive action. This spatial criterion is more informative than scalar metrics such as DCPA and TCPA, which do not capture the directional asymmetry of navigational danger. Szlapczynski et al. (2018) demonstrated a particularly practical application: using a dynamic domain model to determine the latest feasible moment at which a give-way manoeuvre can still be performed while guaranteeing no domain violation.

4.3. Near-Miss Detection and Collision Alert Systems

The increased usage of AIS data has created an opportunity to retrospectively identify near-miss events at a scale previously unavailable. SSD models provide the natural criterion for such detection: a near-miss can be operationally defined as an encounter in which the domain of one or both vessels was violated. Szlapczynski and Szlapczynska (2021) formalised this approach through a domain-based collision risk model that introduces structured temporal parameters enabling not only binary near-miss classification but continuous risk quantification throughout the evolution of a close-quarters situation. This framework supports both offline accident investigation and real-time collision alert systems.

4.4. Autonomous Navigation and MASS

The application of domain theory to autonomous navigation is both the most recent and most consequential of the five areas surveyed in this paper. MASS collision avoidance systems require spatial safety criteria that can be evaluated algorithmically in real time, and the SSD is a natural candidate. However, most existing models were calibrated on human navigational behaviour. An autonomous system requires a domain model grounded not in human preference but in physical and regulatory constraints: minimum stopping distances, give-way vessel obligations, sensor detection ranges, and actuator response times. Developing domain models adequate to this requirement is one of the central challenges identified by Li et al. (2025) and defines much of the current state of research.

5. Discussion

5.1. Model Diversity and Standardization

A striking feature of fifty years of ship domain research is that it has produced a large and growing number of models without converging on a single accepted standard. Domain shapes range from circles to complex dynamic polygons. Methodologies span empirical observation, expert elicitation, neural networks, and probabilistic inference. Domain dimensions vary considerably across studies. This diversity is sometimes treated as a deficiency of the field, but it more accurately reflects the genuinely context-dependent nature of navigational safety. A domain appropriate to a large container vessel navigating a deep-water strait in open weather will necessarily differ from one appropriate to a coastal ferry in a TSS, or a river barge in a confined fairway. The absence of a universal model is evidence that no universal model exists to be found.

What would be valuable, and what the field still largely lacks, is a systematic framework for selecting and calibrating domain models for specific operational contexts. Progress has been made in identifying the key factors, such as vessel type and size, speed, water area type, traffic density, visibility, and weather, and their relationships with domain dimensions, but a comprehensive, operationally validated framework remains an open research priority.

5.2. Subjectivity, Objectivity, and the Declarative-Effective Gap

The tension between subjective (declarative) and objective (effective) domains reflects a deeper ambiguity about what a ship domain is for. If the domain is intended to capture what navigators do, the effective domain is the appropriate measure. If it is intended to specify what they should do, a normative declarative domain may be more appropriate. The two concepts serve different analytical purposes and should not be combined. Wielgosz and Pietrzykowski (2022) demonstrated that the effective domain is systematically smaller than the declarative domain, with a factor that varies with relative bearing. This has practical implications: risk assessment should use effective domain estimates calibrated on real traffic data, while safety regulation may appropriately draw on the more conservative declarative domain as a minimum clearance standard.

5.3. Implications for MASS

The availability of large-scale AIS data has been the single most useful development in SSD research of the past two decades, enabling global-scale comparative analyses of genuine navigational behaviour (Hörteborn et al., 2019). At the same time, AIS-based domain studies have important limitations. AIS records what ships did, not what they intended to do. It brings together competent navigation with poor navigation, good visibility with fog, and routine encounters with genuinely close-quarters situations. The assumption that observed passing distances represent safe passing distances may be violated in high-traffic waterways or under conditions of high traffic pressure, raising questions about the representativeness of empirically derived domain estimates. The development of MASS brings one of the biggest conceptual challenges to the field. Most existing domain models are based on how OOWs navigate, and they rely, often without stating it outright, on assumptions about how OOWs maintain situational awareness and make decisions in uncertain conditions. These assumptions don't easily apply to autonomous systems. Instead, the operational domain of an autonomous ship needs to be built from the ground up, taking into account vessel dynamics, sensor capabilities, COLREGs requirements, and the levels of risk defined by designers and regulators, rather than relying on patterns of human behaviour.

5.4. Future Directions

Several promising directions emerge from the literature. Probabilistic and dynamic domain formulations are particularly well suited to autonomous applications because they can represent uncertainty in target ship behaviour and environmental conditions in a computationally available form. The integration of domain theory with formal risk frameworks expressed in terms of collision probability and regulatory compliance would provide a principled basis for calibrating autonomous collision avoidance systems. Additionally, the development of three-dimensional domain models that account for underwater obstacles, shallow water effects, and hydrographic constraints will be necessary as autonomous operations extend to complex coastal and port environments.

6. Conclusion

This paper has brought the conceptual development of SSD models from their origins in Japanese maritime traffic engineering research in 1971 through to the most recent systematic reviews in 2025. The following principal conclusions can be drawn.

First, the SSD has evolved across three broad phases: an empirical-statistical phase (1970s–1980s) grounded in traffic surveys and radar data; an analytical and knowledge-based phase (1990s–2010s) characterised by fuzzy boundaries, unified analytical frameworks, and neural network-based models; and a data-driven and autonomous phase (2010s–present) defined by large-scale AIS exploitation and the imperative to adapt domain theory to MASS contexts.

Second, the diversity of domain models in the literature reflects the genuine context-dependence of navigational safety rather than a lack of scientific rigour. No universal domain model exists, but this is not even expected. What is needed is a context-sensitive framework for model selection and calibration, supported by empirically grounded relationships between operational parameters and domain dimensions.

Third, the conceptual distinction between declarative and effective domains is not merely a methodological problem but has consequences for risk assessment, system design, and regulatory settings. Both concepts have legitimate roles, and mixing them leads to analytical errors.

Fourth, the MASS transition represents a genuinely novel problem that cannot be solved by extrapolating from domain models based on human behavior. The development of autonomous-system-appropriate domain frameworks grounded in vessel dynamics, sensor performance, COLREGs obligations, and formal risk criteria is the defining research priority of the current period.

Finally, significant gaps remain: no internationally agreed domain-based safety standard exists for either manned or autonomous ships; the relationship between domain violations and actual collision outcomes has not been fully characterized. Three-dimensional domain extensions remain underdeveloped. Addressing these gaps will be essential if ship domain theory is to fulfil its potential as a foundation for future maritime safety systems.

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Development of an Innovative Training Module for Automation in the Ship's Bilge Pumping System

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Abstract: The rapid advancement of maritime automation necessitates hands-on training for marine engineers, particularly concerning critical operations such as the ship's bilge pumping system. Currently, the idealized nature of virtual simulators and limited access to functional equipment constrain the development of operational competency. This study addresses this pedagogical gap by designing, fabricating, and evaluating an innovative training module for automated bilge pumping systems. Integrating mechanical, electrical, and electronic components, the physical module simulates real-world operations, facilitating direct interaction with pumps, sensors, and control logic. Utilizing a developmental research design, the module was constructed via systematic fabrication and 3D modeling. Quantitative evaluation through operational trials and expert assessments confirmed the system's high reliability, accuracy, safety, and durability. Results indicate that the module effectively replicates shipboard operations and is highly suitable for instructional use. Ultimately, by providing a functional hardware platform designed to bridge the gap between theory and application, this module may improve maritime education.

Keywords: maritime education; bilge pumping system; automation training; experiential learning

1. Introduction

The maritime sector requires highly qualified professional seafarers, notably marine engineers, to ensure the safe and effective operation of vessels. As technology evolves and integrates into all aspects of daily life, education systems worldwide recognize the need to equip students with the skills necessary to navigate this digital landscape. Ramaila and Molwele (2022) state that competencies and skills in the classroom continue to be a crucial strategic requirement for the coherent development of modern maritime professionals.

According to Demirel (2020), the operation of the marine industry is changing significantly due to digitalization and elevated levels of automation, which makes the role of the seafarer more vital than ever. Under the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW), the basic requirements for maritime education and training (MET) are established (Türkistanli, 2024). However, with the onset of the fourth industrial revolution, a discrepancy exists between awareness and practical action in current pedagogy (Simanjuntak, 2024).

The lack of practical module kits in maritime education can seriously impair students' skill development. Without physical models, students are deprived of the experiential learning essential for comprehending intricate machinery like the bilge pumping system. Rosnelli and Ristiana (2023) highlight that training management models that utilize practical module kits allow for superior training strategies and high-quality feedback compared to purely theoretical instruction. This study addresses the lack of interactive resources by developing a module that bridges the gap between abstract theory and real-world practice.

As technology evolves and integrates into all aspects of daily life, education systems worldwide recognize the need to equip students with the skills necessary to navigate and contribute to this digital landscape. Ramaila and Molwele (2022) state that competencies and skills in the classroom continue to be a crucial strategic requirement. Creative instructional techniques that integrate technology in developing students' skills and competencies are necessary to help ensure effective teaching and learning.

The operations of the marine industry are changing significantly due to digitalization and elevated levels of automation, which also makes seafarers' roles more vital to consider (Demirel, 2020); hence, a highly

qualified and specialized workforce prepared to adopt constantly changing technologies is required in the increasingly technological shipping industry. Instead of just preparing students for the demands of the present, educational institutions aim to prepare them for the future. They must embrace new initiatives and recognize the advantages of IT technology in addition to the impact that digitalization has on the sector to enhance their pedagogy.

The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), first adopted in 1978, has established globally recognized standards for maritime education and training (MET), ensuring the competence and mobility of seafarers worldwide. The maritime industry continues to evolve through rapid technological advancements, digitalization, and the Fourth Industrial Revolution. Likewise, the STCW Convention must continue to adapt to ensure that MET remains relevant, responsive, and aligned with emerging industry demands (Türkistanli, 2024).

The study aimed to develop an innovative training module for ship bilge pumping systems to aid the students in setting up a transfer system and operating different components of the pumping system, giving them hands-on experience with various electrical components, such as motors, circuit breakers, and contactors, as well as electronic devices that enable automated system operation, including sensors, relays, and converters. This experiential learning approach enhances students' understanding, knowledge transfer, and long-term retention by allowing them to interact directly with actual equipment. Specifically, this study is designed to accomplish the following objectives: (1) To design and fabricate an interactive training module, (2) To assemble the training module, (3) To test the functionality of the training module according to the different setups available.

2. Methodology

2.1 Research Design

This study employed a developmental research design to create the practical module kit. According to Richey, Klein, and Nelson (2004), developmental research is the systematic study of designing, developing, and evaluating instructional products that must meet criteria of internal consistency and effectiveness. A quantitative approach was utilized to conduct functionality tests and gather expert evaluations.

2.2 Development Process

The study started with the preparation, determining and selection of appropriate materials needed to design different areas of the system, such as mechanical systems, power circuits, and control circuits. Subsequently, the different components of the training module, such as the block diagram (Figure 4), circuit diagram, 3D model design, and program code (Figure 3) were completed. Each component underwent a series of tests and loads to ensure its readiness for the training module.

After verifying the functionality of each component, the training module was carefully assembled as specified in the plan. Upon completion, it was subjected to a functionality test according to the different setups applicable to the training module.

2.3 Hardware Specifications

The designed training module comprised the following mechanical and electrical/electronic components (Figure 1).

The first mechanical component is the Pump Set with Motor, which served as the main equipment in the transfer system. It comprises a centrifugal pump with a flow capacity of 5 m3/h, powered by a 220V three-phase motor.

Second are the Tanks (four tanks in all) that serve as liquid storage during the transfer process. The tanks are made of acrylic sheets: 2 '× 3', 10mm, clear, and 1 '× 2', 10mm, clear.

Then there is the clear 25 mm ball valve, which controls the flow of the liquid in the system by permitting, regulating, or stopping its passage.

The fourth component is the 25 mm, 1 m tube/pipe, a hollow tube through which the liquid flows. This pipe is made of acrylic materials that enable users to observe the movement of the liquid, making it suitable for instructional and demonstration purposes.

Next is the flow meter, which monitors the flow of the liquid inside the system. The monitoring capacity of the flow meter is 10 gallons per minute.

The last mechanical component is the pressure gauge/compound gauge, attached to different parts of the system to monitor pressure at specific points. A compound gauge is used to measure vacuum pressure, while a pressure gauge is used to measure positive pressure.

Moreover, the training module is composed of the following electrical and electronic components:

The circuit breaker is the primary protection of the system, which breaks the electric circuit when it detects an excessive current. This prevents damage to the electrical components and increases the overall safety and reliability of the transfer system.

The system also has normally open (NO) and normally closed (NC) switches for various motor control operations. These switches enable users to start, stop, and control various sequences of operation and demonstrate basic principles of motor control.

The lamp indicators are provided for visual indication of the operating status of the system. They monitor power availability, operation, and control conditions of the equipment, which improves system monitoring and troubleshooting.

An audible buzzer is incorporated in the system to alert the users whenever a fault or abnormal operating condition occurs. This warning device enhances operational safety by providing immediate notification of system malfunctions.

The next components are the relays and contactors, which control the operation of motors and other actuators by establishing and interrupting electrical connections as required (Figure 2). These components enable safe and efficient switching of electrical loads while supporting various control configurations.

Finally, microcontrollers process input signals to produce the output signals required for the automatic operation of the different components of the transfer system.



Figure 1. Completed training module for automation in the ship’s bilge pumping system.

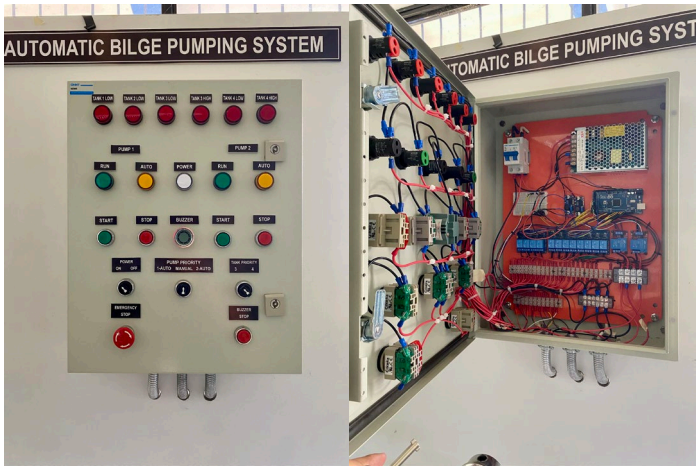


Figure 2. Training module control and alarm panel.



```
il11b | Arduino IDE 2.3.6
Sketch  Tools  Help
Arduino Mega or Meg...
etch_jul11b.ino
210  void handleModeChange() {
211    if (currentMode != previousMode) {
212      if (previousMode == MODE_P1_AUTO_P2_MANUAL && currentMode != MODE_P1_AUTO_P2_MANUAL) {
213        digitalWrite(PUMP_1_RELAY_PIN, RELAY_OFF);
214        pump1_manual_state = false;
215      }
216      if (previousMode == MODE_P1_MANUAL_P2_AUTO && currentMode != MODE_P1_MANUAL_P2_AUTO) {
217        digitalWrite(PUMP_2_RELAY_PIN, RELAY_OFF);
218        pump2_manual_state = false;
219      }
220    }
221  }
222
223  void handlePumpLogic() {
224    if (currentMode == MODE_P1_AUTO_P2_MANUAL) {
225      bool isTank3Priority = digitalRead(TANK_PRIORITY_SWITCH_PIN) == LOW;
226      runAutoPump(PUMP_1_RELAY_PIN, isTank3Priority ? distance3 : distance4);
227    } else {
228      runManualPump(PUMP_1_RELAY_PIN, PUMP1_START_BUTTON_PIN, PUMP1_STOP_BUTTON_PIN, &pump1_manual_state, &p1_start_last, &p1_stop_last);
229    }
230
231    if (currentMode == MODE_P1_MANUAL_P2_AUTO) {
232      bool isTank3Priority = digitalRead(TANK_PRIORITY_SWITCH_PIN) == LOW;
233      runAutoPump(PUMP_2_RELAY_PIN, isTank3Priority ? distance3 : distance4);
234    } else {
235      runManualPump(PUMP_2_RELAY_PIN, PUMP2_START_BUTTON_PIN, PUMP2_STOP_BUTTON_PIN, &pump2_manual_state, &p2_start_last, &p2_stop_last);
236    }
237  }
238
239  void runAutoPump(int pumpRelayPin, float tankDistance) {
240    if (tankDistance >= AUTO_PUMP_START_CM) {
241      digitalWrite(pumpRelayPin, RELAY_ON);
242    } else if (tankDistance <= AUTO_PUMP_STOP_CM) {
243      digitalWrite(pumpRelayPin, RELAY_OFF);
244    }
```

Figure 3. Arduino sketch, program code.

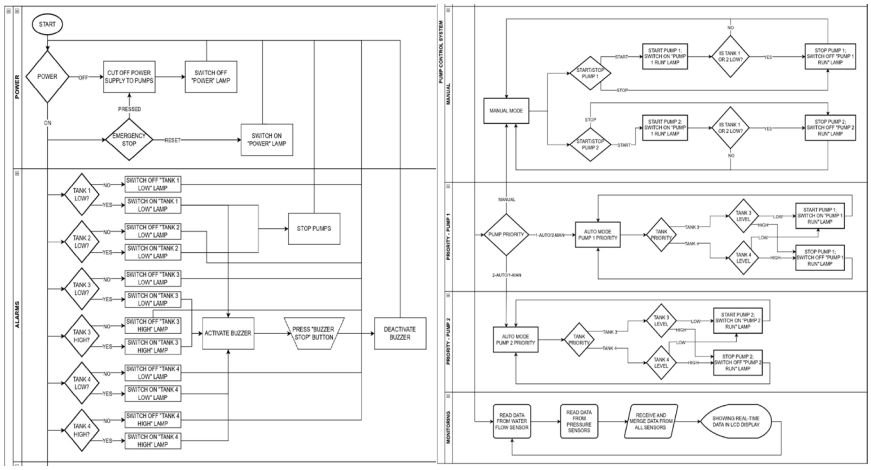


Figure 4. Program flow.

2.4 Functionality Test

In a series of trials, descriptive statistics were used to evaluate the functionality of individual components and the overall training module.

The mean, a central tendency metric that provides insight into the average or typical value within a dataset (Garza and Launico, 2026), was used to assess the reliability, accuracy, adjustability, safety features, and durability of the equipment while operating it.

To ensure the validity and reliability of the training module, an expert evaluation was conducted by a panel of selected maritime instructors, including a seasoned Chief Marine Engineer with more than 20 years of seafaring experience and 4 years as a maritime college instructor, a marine engineer for 12 years with 11-year experience as a maritime college instructor, and a licensed Electronics and Communications Engineer (ECE) with 3 years of experience as a maritime college instructor.

The training module was operated under three different set-ups: single-pump operation, two pumps in series, and two pumps in parallel, during which most components were operational and part of the functionality test. Each evaluator was given the functionality checklist for each set-up. The three evaluators then operated the training module. This ensured that the evaluators could assess the reliability, accuracy, adjustability, safety features, and durability of the training module in different set-ups.

The evaluation was done using the following scale and interpretation (Table 1) and yielded the following results (Table 2).

Table 1. Mean score range.

Mean score range		Interpretation	Description
4.21	5.00	Excellent	The prototype operates flawlessly; all functions perform as intended with no observed issues or delays.
3.41	4.20	Very Good	The prototype operates well with only minor, non-critical issues; functionality is reliable and consistent.
2.61	3.40	Good	The prototype shows moderate operability; some functions work properly, but occasional issues are present.
1.81	2.60	Fair	The prototype has significant operability problems; several functions are unreliable or difficult to use.
1.00	1.80	Poor	The prototype is largely inoperable; major functions fail, or it is not usable under expected conditions

Table 2. Prototype features measurement.

Features	N	Mean	SD	Interpretation
Reliability	9	4.86	.08	Excellent
Accuracy	9	4.80	.08	Excellent
Adjustability	9	4.80	.14	Excellent
Safety Features	9	4.73	.12	Excellent
Durability	9	4.73	.13	Excellent

The results show that the prototype received positive expert ratings across several crucial features that were evaluated during the evaluation process.

One of these characteristics is reliability, which is the capacity of the prototype to function consistently and dependably under extended or repeated use without breaking down or performing worse. The high ratings in this category imply that the prototype's performance in practical applications can be relied upon (Zurek *et al.*, 2020).

The prototype's first area of strength was accuracy, which shows it can perform tasks or measurements with high precision and minimal error. This guarantees that the results generated match the anticipated results, which is crucial for applications that need precise performance (Piedra-Cascón *et al.*, 2020).

Additionally, the prototype demonstrated a high degree of adjustability, meaning it could be readily adjusted or calibrated to accommodate various user preferences, operational settings, or environmental circumstances. This adaptability makes it more useful in a variety of situations and more practical (Srivastava and Bai, 2022).

Regarding safety features, the assessment revealed that the prototype had integrated safeguards to shield users from possible injury while in use. These include fail-safe mechanisms, alarm systems, secure enclosures, and automatic shut-offs, all of which help reduce the risk of mishaps and ensure a safe user experience (Raheemy, Sherratt and Hallowell, 2025).

Finally, the prototype was found to be extremely durable, indicating it was constructed with components and design features that would enable it to withstand wear, tear, and environmental stress over time (Gengrinovich, 2024). This quality is essential for maintaining cost-effectiveness and long-term performance, particularly in challenging settings.

When combined, these outcomes demonstrate the prototype's overall quality and show that it is a well-thought-out, highly functional, and user-centered invention ready for deployment or further development.

4. Conclusion

The evaluation results indicate that the prototype is a well-rounded and high-performing innovation. Its outstanding precision, durability, safety, adjustability, and dependability show how well suited it is for practical use. The prototype ensured user safety, produced accurate data, reacted well to changing conditions, and endured operational and environmental stress. It also continuously worked without failure. Together, these characteristics demonstrate that the prototype is not only technically sound but also useful and user-friendly. As a result, it is well positioned to be improved, used more widely, or scaled.

This study is limited to the design, fabrication, assembly, and functional testing of the interactive training module, as stated in its objectives, and does not include its implementation in actual classes or the assessment of student learning outcomes. A subsequent study is recommended to evaluate the module's effectiveness in enhancing student learning and achieving the intended educational outcomes through classroom application.

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Integrating Eye-Tracking into Human-Centred Evaluation of Bridge Ergonomics and Navigation System Interfaces

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Abstract: The rapid digitalization of maritime navigation has significantly changed both ship operations and maritime education. Integrated Navigation Systems (INS), with Electronic Chart Display and Information Systems (ECDIS) at their core, now dominate bridge environments and simulator-based training. As these systems become more complex, the challenge for maritime universities and training institutions is no longer limited to teaching procedural competence, but also to developing students' ability to interpret digital navigation information efficiently and safely. In this context, bridge ergonomics and interface usability emerge as critical educational factors influencing situational awareness, cognitive workload, and decision-making performance. This paper explores the use of eye-tracking technology in maritime navigation, with particular emphasis on visual attention, gaze behavior, situational awareness, human–machine interfaces, mental workload, and its potential contribution to training optimization. The simulator environment provides a safe and repeatable platform for exposing trainees to ergonomic challenges that would be difficult to isolate during real-world navigation. The practical implications of this research are directly relevant to maritime universities and training centers. Eye-tracking findings can contribute to the development of human-centered training methodologies that align technological advancement with educational effectiveness, supporting the preparation of future officers for safe operation of modern navigation systems.

Keywords: maritime education and training; eye-tracking; bridge ergonomics

1. Introduction

The rapid digitalization of maritime navigation has fundamentally transformed both operational practices at sea and the structure of maritime education and training. Modern ship bridges are increasingly dominated by Integrated Navigation Systems (INS), which integrate information from various sources such as ARPA, AIS, and ECDIS to support navigational decision-making (International Maritime Organization, 2007). Although these technologies improve the availability and integration of navigational data, they also create challenges related to information complexity, interface usability, and human-machine interaction (International Maritime Organization, 2019). This complexity can impose significant cognitive demands, potentially leading to information overload and increased risk of error in challenging navigational situations (Vu, Lutzhoft and Imset, 2022)

Despite continuous technological advancements and regulatory efforts aimed at improving navigational safety, human factors remain a dominant contributor to maritime incidents (Hetherington, Flin and Mearns, 2006). A substantial proportion of accidents is still attributed to human and organizational factors, often linked to misinterpretation of information, inadequate situational awareness, or suboptimal decision-making under time pressure (Grech, Horberry and Koester, 2019). In this context, the role of interface design and bridge ergonomics has become increasingly important. Modern navigation systems do not merely support decision-making; they actively shape how information is perceived, processed, and acted upon by navigators.

As navigation systems evolve in functionality, their interfaces have become more complex, often requiring users to manage multiple layers of information, alerts, and visual representations simultaneously. This increased complexity places additional cognitive demands on operators, particularly in dynamic and high-risk environments. For maritime education and training institutions, this shift introduces a critical challenge: it is no longer sufficient to train students in procedural system operation alone. Instead, emphasis must also be placed

on developing the ability to efficiently interpret digital information, maintain situational awareness, and manage cognitive workload in technologically advanced bridge environments.

Bridge simulators play a central role in addressing this challenge, providing a controlled and repeatable environment in which trainees can be exposed to realistic navigational scenarios (Sellberg, 2017). However, traditional assessment methods in simulator-based training are often limited to observable performance outcomes, such as task completion or compliance with procedures. These approaches provide limited insight into the underlying cognitive and perceptual processes that drive operator behaviour. In particular, instructors typically lack direct access to information about how trainees allocate visual attention, which elements of the interface they focus on, and how they scan complex displays during navigation tasks.

Eye-tracking technology offers a promising solution to this limitation by enabling the objective measurement of visual attention and gaze behaviour. By capturing data such as fixation duration, gaze distribution, and scan paths, eye-tracking provides detailed insight into how navigators interact with digital interfaces in real time (Duchowski, 2007). This technology has been successfully applied in various high-risk domains, including aviation, automotive systems, and medicine, to evaluate human performance, interface usability, and cognitive workload. In maritime contexts, its application is growing, particularly in studies focusing on situational awareness, workload assessment, and differences between novice and expert operators.

However, existing research in maritime eye-tracking remains largely fragmented, often addressing isolated aspects of human performance rather than providing an integrated perspective. Furthermore, relatively limited attention has been given to the role of eye-tracking within the context of maritime education and training. There is a need to better understand how insights derived from visual behaviour can be systematically incorporated into training methodologies, simulator design, and instructional practices.

This paper discusses the integration of eye-tracking technology into the human-centred evaluation of bridge ergonomics and navigation system interfaces, with a particular emphasis on its application in maritime education and training. Drawing on existing literature, the paper examines how insights from visual attention and gaze behaviour can support the assessment of interface usability, the development of situational awareness, and the enhancement of training effectiveness in simulator-based environments. By linking human factors research with pedagogical objectives, the paper proposes a conceptual framework for leveraging eye-tracking as a tool for improving both the design of navigation systems and the training of future maritime professionals.

2. Human Factors and Ergonomics in Maritime Navigation

Human factors play a central role in maritime safety, as navigation remains a complex socio-technical process in which human operators interact continuously with advanced technological systems. Despite significant progress in navigational equipment and regulatory frameworks, human and organizational factors continue to account for the majority of maritime incidents (Apostol-Mates and Barbu, 2016). This highlights the need to better understand how human performance is influenced not only by training and procedures, but also by the design of the systems that support decision-making on the bridge.

In modern bridge environments, the concept of ergonomics extends beyond physical layout to include cognitive ergonomics, which focuses on how information is perceived, processed, and acted upon by the operator (Grech, Horberry and Koester, 2019). Navigation systems such as Integrated Navigation Systems (INS) and Electronic Chart Display and Information Systems (ECDIS) present large volumes of dynamic information through complex visual interfaces. While these systems are designed to enhance situational awareness, their increasing complexity can also impose additional cognitive demands on navigators, particularly in time-critical situations (May, 1999).

Situational awareness, as defined by Mica Endsley (1995), consists of three levels: perception of elements in the environment, comprehension of their meaning, and projection of their future status. In maritime navigation, effective situational awareness depends heavily on the operator's ability to efficiently extract relevant information from multiple displays and integrate it into a coherent mental model of the surrounding environment (Sandhåland, Oltedal and Eid, 2015). Poor interface design, excessive information density, or inadequate visual hierarchy can disrupt this process, leading to reduced awareness and increased likelihood of error (Bjorneseth *et al.*, 2014).

Research in cognitive workload further supports the importance of ergonomic design in navigation systems. High levels of workload have been associated with reduced attention allocation, slower decision-making, and

increased error rates (Hart and Staveland, 1988). In digitally intensive bridge environments, workload is often influenced not only by external factors such as traffic density or weather conditions, but also by the usability of the interface itself (Hareide and Ostnes, 2017). Inconsistent layouts, unclear symbology, and inefficient alerting mechanisms can require additional cognitive effort, diverting attention from critical navigational tasks.

The importance of standardized and human-centred interface design has been formally recognized by the International Maritime Organization, particularly through the introduction of MSC.1/Circ.1609 guidelines (International Maritime Organization, 2019). These guidelines emphasize the need for consistency in layout, symbols, and interaction logic across navigation equipment, aiming to reduce cognitive load and improve the usability of systems such as INS, ECDIS, and radar. However, despite these efforts, variations between manufacturers and legacy design approaches continue to result in inconsistencies that may negatively affect operator performance.

In this context, bridge ergonomics should be understood as a critical factor in shaping the interaction between human operators and navigation technology. Rather than being a secondary design consideration, ergonomics directly influences how information is interpreted, how attention is allocated, and ultimately how decisions are made in operational settings (Porathe, 2006). For maritime education and training, this implies that developing navigational competence must include not only technical proficiency, but also the ability to effectively interact with and interpret complex digital interfaces under varying operational conditions. Bridge simulators provide a controlled and repeatable environment in which these skills can be developed, yet traditional assessment methods often remain limited to observable performance outcomes and offer limited insight into the underlying perceptual and cognitive processes.

3. Eye-Tracking in Maritime Research

Eye-tracking technology has emerged as a valuable tool for analyzing human interaction with complex systems by providing objective measurements of visual attention and gaze behaviour (Holmqvist *et al.*, 2011). In contrast to traditional observational or performance-based assessment methods, eye-tracking enables researchers to directly examine how operators visually engage with their environment, offering insights into underlying cognitive processes that are otherwise difficult to capture (Muczyński *et al.*, 2013). Metrics such as fixation duration, saccades, scan paths, and pupil dilation provide quantitative indicators of attention allocation, information processing, and mental workload (Duchowski, 2007)

Originally developed and widely applied in fields such as aviation, psychology, and human–computer interaction, eye-tracking has been adopted in maritime research. Its application is particularly relevant in bridge environments, where operators must continuously monitor multiple information sources and make time-critical decisions. By capturing visual behaviour in real time, eye-tracking allows for a detailed analysis of how navigators interact with navigation systems, identify relevant cues, and respond to dynamic situations.

Several studies have applied eye-tracking methods to investigate visual scanning patterns and situational awareness in maritime navigation. For example, research by Hareide and Ostnes (2017) demonstrated that eye-tracking data can reveal inefficiencies in user interaction with navigation interfaces, highlighting areas where operators spend excessive time searching for information. Similarly, Atik and Arslan (2019) assessed ship officers' competency in electronic navigation using eye-tracking data and found significant differences between expert and novice officers. Their findings showed that experts exhibit more structured and efficient visual scanning patterns. In a related study, Atik (2020) examined situational awareness during Bridge Resource Management training and demonstrated that eye-tracking provides valuable insights into officers' focus of attention, offering considerable potential for improving training effectiveness.

In addition to visual scanning, eye-tracking has been used to assess cognitive workload and attentional demands during navigation tasks (Yan, Wei and Tran, 2019). Changes in fixation patterns and pupil size have been associated with increased mental effort, particularly in complex or unfamiliar scenarios (Orlandi and Brooks, 2018). Such findings are consistent with broader research in cognitive ergonomics, suggesting that visual attention is closely linked to cognitive processing and decision-making performance. In maritime contexts, this relationship is especially important, as excessive workload or poorly distributed attention can lead to reduced situational awareness and increased risk of error (Bjørneseth *et al.*, 2012).

Recent maritime eye-tracking research has expanded beyond the analysis of basic visual scanning patterns and has increasingly addressed navigational performance, situational awareness, workload, seafarer perception,

and maritime training. Uflaz et al. (2023) combined a review of eye-tracking applications in maritime operations with a pilot bridge-simulator study involving 13 participants. Using Tobii Glasses 3 and predefined areas of interest on critical bridge equipment, the study examined fixation behaviour, saccades, pupil size, and visual attention across different bridge displays. The pilot results indicated that radar received the highest level of visual attention, followed by visual displays and the upper display unit.

Khalique et al. (2023) examined the influence of multifunction displays on visual lookout performance during nocturnal navigation and used eye-tracking in both real-world and simulator-based bridge environments. Kitamura et al. (2024) investigated gaze movement and risk perception in screen-based operation of Maritime Autonomous Surface Ships. Petrović and Vujičić (2025) compared seafarers' perceived and actual use of visual observation, radar, and ECDIS during simulated navigation, while bin Kamarumtham and Murai (2025) proposed video-based gaze similarity analysis for assessing perceptual performance and comparing the gaze behaviour of seafarers with different levels of experience.

Taken together, these studies demonstrate that recent maritime eye-tracking research is developing in several complementary directions, including visual attention assessment, navigational performance, workload analysis and maritime training. However, the existing approaches generally focus on specific methodological or operational questions. A defined framework that connects eye-tracking-based visual behaviour assessment with navigational performance, bridge interface ergonomics, simulator-based training, structured debriefing, and subsequent improvement of training strategies or interface design remains insufficiently developed. The present paper addresses this gap by proposing a conceptual framework that integrates these elements within a common human-centred evaluation process.

4. Proposed Conceptual Framework for Eye-Tracking in Maritime Education

The increasing complexity of modern navigation systems has significantly reshaped the demands placed on maritime education and training. Traditional approaches, which primarily focus on procedural knowledge and compliance with established navigation practices, are no longer sufficient in environments dominated by digital interfaces and integrated systems. Instead, there is a growing need to develop higher-level competencies related to information interpretation, visual attention management, and situational awareness in complex, technology-rich bridge environments.

Bridge simulators have become a central tool in addressing these challenges, providing controlled and repeatable conditions for training and assessment. Within simulator-based training, instructors typically evaluate performance based on observable outcomes, such as adherence to procedures, task completion, and decision-making results. However, these methods offer limited insight into the underlying cognitive and perceptual processes that shape trainee behaviour. In particular, they do not provide direct information about how trainees allocate visual attention, how they scan navigation displays, or which elements of the interface they prioritise during critical tasks.

Eye-tracking technology offers a powerful means of addressing these limitations by enabling the direct observation and quantification of visual behaviour. As demonstrated in previous maritime studies, eye-tracking can reveal differences in scan patterns between novice and experienced navigators (Li *et al.*, 2020), identify inefficient search strategies (Hareide and Ostnes, 2017), and highlight areas of interface design that may contribute to confusion or increased cognitive load (Yan, Wei and Tran, 2019). These capabilities make eye-tracking particularly valuable in educational contexts, where understanding how a trainee interacts with information can be as important as evaluating the final outcome of their actions.

Eye-tracking can also support simulator-based debriefing by visualising gaze behaviour and enabling targeted feedback on visual strategies, attention allocation, and situational awareness (Jarodzka *et al.*, 2013; Atik, 2020). Comparing trainee gaze behaviour with expert or expected patterns can support reflective learning and help identify missed cues, delayed responses, or over-reliance on specific information sources (van Gog and Scheiter, 2010).

Eye-tracking can further inform the design and evaluation of training scenarios. Analysing trainee interaction with different interface configurations, lighting conditions, and levels of task complexity can support the development of targeted training modules that address visual scanning strategies and situational awareness in addition to procedural correctness (Hareide and Ostnes, 2016).

Building on these insights, this paper proposes a conceptual framework for the systematic integration of eye-tracking into maritime simulator-based education and training. The framework consists of three interconnected components:

- Measurement of visual behaviour during simulator exercises using eye-tracking technology to capture real-time data on gaze patterns, fixations, scan paths, and pupil dilation.
- Analysis of gaze metrics in relation to task performance, interface characteristics, and individual differences (e.g., novice vs. expert), with particular focus on identifying ergonomic strengths and weaknesses of navigation systems such as ECDIS and INS.
- Application of findings to training design, debriefing practices, and instructional strategies. This includes the use of gaze visualizations (heatmaps, scan paths) during debriefing sessions to support reflective learning, the development of targeted training modules for improving visual scanning strategies, and feedback loops that inform both trainee development and future interface design.

The novelty of the proposed framework lies not in the use of eye-tracking alone, but in its integration into a closed-loop, human-centred process. It links objective gaze measurement with the analysis of interface ergonomics and task performance, and translates the findings into debriefing, targeted training, and feedback for improving simulator scenarios and navigation-system interfaces. Its scientific contribution is a structured bridge between human-factors assessment and maritime education, while its practical contribution is a repeatable pathway for using gaze evidence to support trainee development and human-centred interface design.

The proposed framework positions eye-tracking not merely as a research instrument, but as a practical educational tool. By making cognitive and perceptual processes visible, it enables more precise feedback and creates a feedback loop between trainee development, system ergonomics, and pedagogical practice.

This conceptual framework, developed within the ongoing SE-NAV project (IP-UNIZD2025-27090), is intended to be evaluated through controlled bridge-simulator experiments involving novice trainees and experienced officers. Participants will complete standardized scenarios representing coastal route monitoring, collision avoidance in high-traffic waters, and hazard detection under different levels of task complexity. During these scenarios, eye-tracking will capture fixation behaviour, time to first fixation, dwell time, scan-path characteristics, and pupil dilation. These measures will be analysed together with objective indicators of navigational performance and situational awareness, including task completion, decision-making, responses to relevant hazards, and SAGAT-based probes.

The analysis will examine differences in gaze behaviour and performance between participant groups, as well as the relationships between visual attention, interface characteristics, and navigational outcomes. Attention will be given to inefficient scanning strategies, missed or delayed attention to critical information, and interface elements associated with increased workload or reduced performance. A multi-criteria decision-making (MCDM) approach will then be used to integrate gaze, performance, and situational-awareness indicators and to rank interface components according to their ergonomic criticality. The purpose of this evaluation is to determine whether the framework can support objective trainee assessment, targeted debriefing, and the iterative improvement of simulator scenarios and navigation-system interfaces.

Furthermore, the framework is adaptable to Maritime Autonomous Surface Ships (MASS), where areas of interest would shift toward fleet-overview displays, automation-status indicators, and alarm management. The framework could be used to evaluate whether operators effectively distribute attention across multiple vessels and detect critical anomalies, applying video-based gaze similarity analysis to assess perceptual performance in autonomous oversight roles. The goal is to support maritime universities and training centers in developing more effective, evidence-based training methodologies that better prepare future officers for safe and efficient operation in modern, digitally intensive bridge environments.

5. Discussion

The integration of eye-tracking technology into the evaluation of bridge ergonomics and navigation system interfaces represents a promising avenue for advancing human-centred approaches in maritime operations and education. As modern Integrated Navigation Systems (INS) and ECDIS become increasingly complex, the ability of navigators to efficiently manage visual attention and maintain situational awareness has emerged as a

critical factor for safety. This paper argued that eye-tracking can serve as a valuable bridge between human factors research and maritime education and training.

The reviewed literature consistently demonstrates that eye-tracking provides objective insights into visual scanning patterns, attention allocation, and cognitive workload that traditional performance-based assessment methods cannot capture. Studies have shown notable differences between novice and experienced operators, with experts typically displaying more efficient and structured gaze behaviour. These findings reinforce the need to complement conventional performance indicators with measures of underlying perceptual and cognitive processes.

The proposed framework addresses these limitations by connecting gaze measurement with interface ergonomics, navigational performance, and practical applications in training and debriefing. By incorporating eye-tracking data into simulator-based training, maritime educators can move beyond procedural training toward more sophisticated, learner-centred methodologies that target visual attention management and situational awareness development.

From an educational perspective, the framework can enhance debriefing through gaze visualizations such as heatmaps and scan paths. These tools can support reflective learning, more precise feedback, and the development of effective visual strategies, while recurring gaze patterns may inform both trainee development and improvements to simulator scenarios and interface ergonomics.

However, several challenges must be acknowledged when considering the practical implementation of this framework. These include technical issues related to eye-tracker calibration and integration in full-mission simulators, the need for standardized metrics and reliable interpretation protocols, the requirement for adequate instructor training, and important ethical considerations concerning data privacy and informed consent.

This conceptual work, conducted within the SE-NAV project (IP-UNIZD2025-27090), represents an important preparatory step toward empirical validation. While the framework is currently based on existing literature and theoretical synthesis, its real value will be tested through future simulator-based experiments. Such studies should examine the relationship between specific interface design features, gaze behaviour, cognitive workload, and training outcomes under realistic navigational conditions.

Ultimately, the successful integration of eye-tracking into maritime education depends not only on technological capabilities but also on the willingness of maritime universities and training institutions to adopt more human-centred and data-informed training practices. By doing so, they can better align educational methodologies with the realities of modern digitally intensive bridge environments, thereby contributing to the preparation of safer and more competent future maritime professionals.

6. Conclusion

This paper presents a conceptual framework for integrating eye-tracking into the human-centred evaluation of bridge ergonomics, navigation-system interfaces, and maritime education. The framework responds to the limitations of conventional assessment by linking visual behaviour with interface ergonomics, navigational performance, training feedback, and future system improvement.

To address these challenges, this paper proposed a conceptual framework for the systematic integration of eye-tracking into maritime simulator-based education and training. The framework consists of three interconnected components — measurement of visual behaviour, analysis of gaze metrics in relation to interface ergonomics and task performance, and practical application of the insights into training design, debriefing, and instructional strategies. By adopting a human-centred approach, the framework positions eye-tracking as both an assessment tool and a powerful instrument for enhancing reflective learning and training effectiveness.

The successful implementation of this framework can contribute to closing the gap between human factors research and pedagogical practice in maritime education. It offers the potential to move beyond procedural training toward the development of higher-order competencies, including efficient visual scanning strategies and robust situational awareness in complex digital environments.

Nevertheless, several challenges remain, such as technical integration in simulator settings, standardization of metrics, instructor training, and ethical considerations related to data collection. This conceptual framework, developed within the ongoing SE-NAV project (IP-UNIZD2025-27090), provides a structured foundation for addressing these challenges through future empirical research.

Eye-tracking technology holds considerable promises for supporting more effective, evidence-based, and human-centred training methodologies in maritime universities and training centres. By making cognitive and perceptual processes visible, it can play a significant role in better preparing future maritime officers for the demands of modern navigation systems and contribute to the broader goal of safer maritime operations.

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Towards Shipping Decarbonization: Experimental Assessment of Hybrid Battery-Fuel Cell Electric Propulsion System

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Abstract: Global decarbonization initiatives with stringent environmental standards necessitate the maritime industry to adopt zero-emission propulsion technologies. This paper reports on an IAMU funded project that experiment the hydrogen as an alternative fuel for decarbonization of the future ships. We present a detailed design, implementation, and testing of a hydrogen fuel cell based electric system for a prototype test vessel. The 5-kW electric motor is supplied with energy from a hydrogen fuel cell as well as a 100 Ah, 48 V lithium iron phosphate battery. This battery aids in power balancing as well as performance enhancement, while the hybrid composition allow reliable continuous output and improved battery life. A safety system for the hydrogen management is consisted of pressure sensors, valves, and valve shutoff. Tests performed in controlled water environments, where data was obtained on motor power, amount of charge taken up by the battery during the tests, speed of the boat through the water, as well as hydrogen consumption within fuel cell. The results indicated stable power delivery with positive dynamics during variable power demand. The system also delivered improved energy efficiency as compared to battery-only systems. Our study shows that for the carbon-free range extension, the hybrid system is optimal. In addition, the project contributed to maritime education and training (MET) competency development of future seafarers by providing hands-on experience in hydrogen fuel cell technology, hybrid energy system integration, safety management, and performance evaluation for future maritime decarbonization applications.

1. Introduction

A radical transformation of the maritime industry is reshaping the industry in response to ever-more stringent global decarbonization mandates and national policies. The urgency for change is underscored by the shipping sector's significant contribution to global greenhouse gas (GHG) emissions. As the result, the shipping sector is under pressure to transit to sustainable propulsion technologies that align with planetary goals in light of international climate commitments. This transformation apart from a compliance issue, presented an opportunity for a shift towards innovation and sustainability, where traditional practices are being challenged by advancements in technology. In this context, the development and adoption of zero-emission propulsion systems have become a precondition for long-term environmental sustainability in maritime operations.

To achieve these ambitious goals, it is essential to explore various technological pathways and alternative fuels that can facilitate the transition to a zero or low-carbon future. Among the alternative fuels hydrogen standing out as a particularly promising option. By integrating hydrogen as a clean energy source into hybrid propulsion systems, the maritime industry can significantly reduce greenhouse gas emissions while enhancing operational efficiency. Hybrid propulsion systems combine different energy sources to optimize performance and minimize environmental impact. The potential for hybrid systems to significantly reduce GHG emissions while maintaining operational efficiency positions them as a critical component in the maritime industry's sustainability strategy.

This study describes the technical analysis of a prototype hybrid electro-hydrogen propulsion system designed for marine applications. The architecture consists of a 5 kW Proton-Exchange Membrane (PEM) fuel cell stack connected in series to a deliver 48 V DC to charge a LiFePO4 battery pack, which is designed for improved power and better energy management performance. PEM fuel cell stacks use electrochemical reactions to convert hydrogen gas stored in a pressurized cylinder into electrical energy, thereby providing clean

electric power with high energy conversion efficiency. In this arrangement LiFePO4 battery serves as an energy buffer to assist in the efficient and timely fulfilling transient power demand. The hybrid system provides smooth load variations that are not sufficiently handled by the fuel cell independently [2]. Many marine propulsion applications benefit from a Permanent Magnet Synchronous Motor (PMSM) that offers outstanding efficiency of the propulsion system over a wide range of speeds and demonstrate excellent dynamic performance characteristics. The PMSM that we specifically developed for this project is driven by a cutting-edge motor controller and has real-time power management algorithms.

The primary control strategy integrated into the design of the PMSM is an energy management system that utilizes the state-of-charge (SOC) to manage the power flow between the fuel cell and battery, maximizing efficiency, extending battery life, and ensuring a steady output during changes in the operating conditions. The hybrid combination of fuel cells and batteries takes advantage of their complementary strengths and mitigates many of the limitations of each technology when used in isolation (such as the limited transient response of the fuel cell and low energy density of the battery). In the maritime environments, Hydrogen storage and handling can be challenging owing to safety concerns, limited space, and operational nature. An integrated safety system was developed to meet the standards and regulations associated with maritime hydrogen handling requirements, including pressure sensors, solenoid valves, and fail-safe shutoff devices. The integrated safety system provides safe storage of hydrogen at high pressures and controlled supply of compressed hydrogen, thus minimizing the hazards associated with handling compressed hydrogen gas (Figure 1).

Testing of the hybrid propulsion system occurred at controlled inland water location to evaluate its performance under the realistic usage conditions. The main parameters measured included propulsion motor power, current, voltage, battery state of charge, boat speed, hydrogen consumption, and thermal profile of the PEMFC stack. The results of the testing provided solid and dependable values for the propulsion power of the hybrid system and had superior transient response characteristics compared with those of battery-powered electric systems with respect to specific energy consumption.

2. System design

With a total length of 5.58 m and a width of approximately 1.75 m, this boat provides a downscaled and stable testing environment for evaluating alternative fuel marine application. With the propulsion system onboard the boat requires a minimum of 1.0 m draft for performing effectively in shallow bodies of water. The hull is constructed FRP, which has a high strength-to-weight ratio and is resistant to corrosion and offers smooth surface. The capacity of the boat hull is designed to carry six passengers; therefore, it is suitable for transporting people or travelling short distances. Figure 1 illustrating by integrating battery and PEM fuel cell propulsion systems into the design, energy-efficient and environmentally sustainable marine operations can be performed.

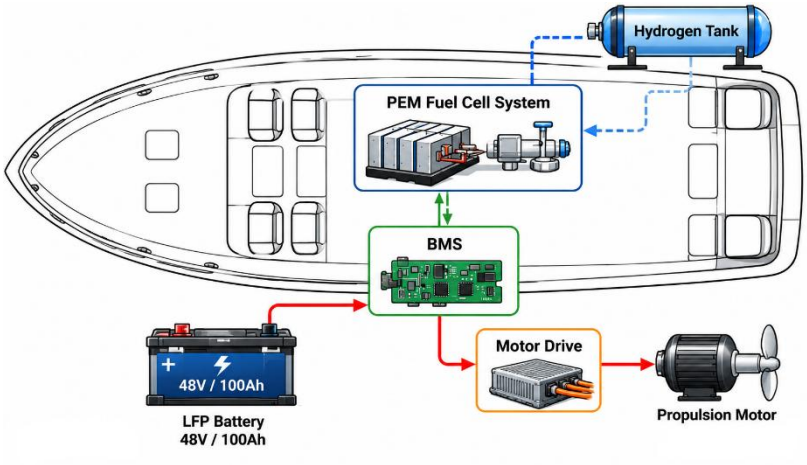


Figure 1. Overview of Electro-Hydrogen Fuel Cell Propulsion System

This propulsion system consists of a 5 kW Proton Exchange Membrane (PEM) fuel cell system operating as a prime mover coupled with a battery. These two energy sources are ideal for meeting transitory performance of the propulsion system. Hydrogen that fuels this PEM fuel cell is stored in a high-pressure tank, and as hydrogen is supplied to the PEM fuel cell system, an electrochemical reaction occurs to produce DC electrical energy, heat, and water. The DC electrical energy and heat from the PEM fuel cell are managed by a

power management system (PMS). The PMS regulates the voltage, stabilizes the output, balances the load between the fuel cell and battery, manages power transmission, and protects against electrical faults to keep the PEM fuel cell operating in the most efficient manner. The battery used is approximately 48 V/100 Ah LFP, being utilised as the primary source of energy storage in the propulsion system, buffering the energy produced by the PEM fuel cell and outputting stable DC power to the motor drive. Continuous monitoring of battery parameters is accomplished by a BMS: voltage, current, temperature, SOC, and State of Health. The BMS also provides cell balancing capabilities and protects against over-charging, deep discharging and thermal problems. The BMS combines with the PMS for effective charging and discharging of the battery. The motor drive receives DC power from the battery and converts it to controlled AC power so that the speed and torque of the propulsion motor can be controlled to provide propulsion in the most efficient manner possible. The propulsion motor then converts the supplied electrical energy into mechanical energy to provide propulsion. The energy flow strategy of the system is battery-dominant, wherein the fuel cell charges the battery, and the motor receives its entire supply from the battery. This separation of the fuel cell and propulsion reduces transient stress on the fuel cell and improves the reliability of the overall system and simplifies the overall control strategies for these devices. With integrated feedback loops with both the BMS, PMS, and motor drive, real-time monitoring, adaptive control with fault detection, and optimal performance and safety are achieved. The architecture results in longer-living fuel cells owing to more consistent operation, improved system stability utilizing battery buffering, and inherent use for marine and varying-speed propulsion applications.

Table 1. Fuel cell and battery technical specification

Parameter	Specification	Parameter	Specification
Fuel Cell Type	PEM Fuel Cell	Energy	5.12 kWh
Rated Power	5 kW	Voltage Range	40–58.4 V
Output Voltage	48 V DC	Cycle Life	2000 cycles
Efficiency	45–55 %	Charging Method	CC–CV
Battery Type	LFP	Charging Current	18A → 13A
Nominal Voltage	51.2 V	Operating Temp	0–50°C
Capacity	100 Ah	IP Rating	IP67

3. Experimental Validation

We performed a series a controlled test in the marine environment and collected data. We utilized the BMS to provide experimental readings to determine factors that help to keep a battery operating safely, efficiently, and reliably. Experimental readings from sensors allow for real-time monitoring of the conditions of an individual cell and the entire pack. These specific parameters will generally include the following: Voltage, Current, Temperatures, SOC and SOH. Therefore, voltage sensors read the individual cell voltages and report this information to the BMS controller. Similarly, current sensors, provide information regarding the charge / discharge of the battery pack. In addition, temperature sensors, such as thermistors, report the cell temperatures or thermal gradients across multiple cells. The BMS controller receives this real-time data from the sensors and uses this information for monitoring the battery and any required report-generating activities.

SOC determination, one of the most essential functions performed by the BMS, is estimated through the measurement of experimental voltage, current, and temperature data with model-based algorithms. The BMS inputs the measured parameters into either an active or passive balancing technique to equalize SOC values among battery cells. This equalization of SOC values increases battery life and performance. The effective implementation of measurement methods, such as real-time temperature monitoring and actual temperature data collection, allows the BMS to execute fail-safe protective measures, such as current isolation, activation of cooling or disconnection from the system under abnormal thermal events to prevent thermal runaway or damage.

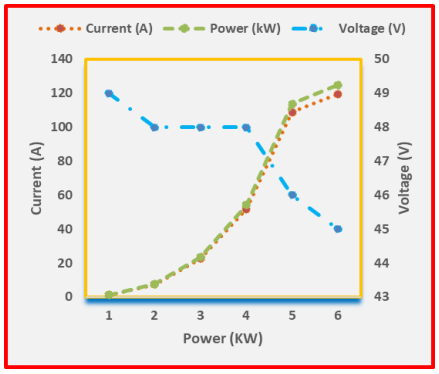


Figure 2 relationships for (power, current, voltage)

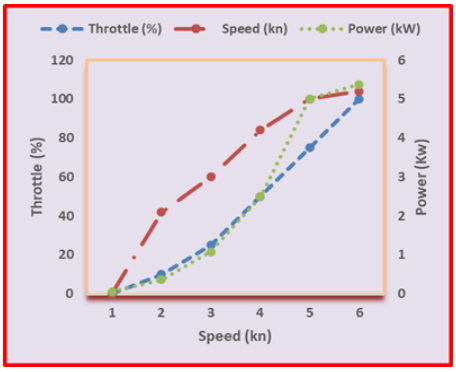


Figure 3 boat's speed and power use in different modes

Figure 2 shows the relationships between power (kW), current (A), and voltage (V). As the power increased from 1 kW to 5 kW, the current increased significantly from nearly zero to approximately 120 A. The positive correlation between power and current indicates that higher power levels are required when higher current levels are needed. As the power increased, the voltage decreased. When power output was 1 kW, voltage was around 49V, and at 5 kW, voltage was around 45V. Thus, the decrease in voltage levels indicates that system power loads are increasing, while voltage levels are decreasing as a result of internal or load independent resistance. Essentially, when power demands increase, current levels will increase, whereas voltage levels will decrease. These relationships are consistent with electrical system adjustments to the load, which will inversely affect the amount of current flow and level of voltage output through the system. Therefore, it is clear that monitoring both current and voltage will assist in maintaining the overall stability and efficiency of the system.

Figure 3 shows how changing the throttle settings affects a boat's speed and power use in different modes. When the boat moves between 1 and 3 knots, it speeds up well. Increasing the throttle from 0% to 25% makes the boat go faster without using much power, about 1.5KW. This low power use means the boat runs efficiently with little water resistance. The boat's hull faces less drag, allowing it to move effectively with less energy. Between 3 and 4 knots, speed and throttle input are almost directly related, but power use rises to 2-3KW due to more water resistance from waves and friction. To go faster, more energy is needed, but the system still balances speed and efficiency. Above 4 knots, power use jumps sharply, reaching 5-6 kW at a top speed of about 6 knots. Even with the throttle nearly at full (up to 100%), speed gains are small because of strong water drag forces. This shows that as the boat nears its speed limit, more throttle means much more energy use with little speed increase.

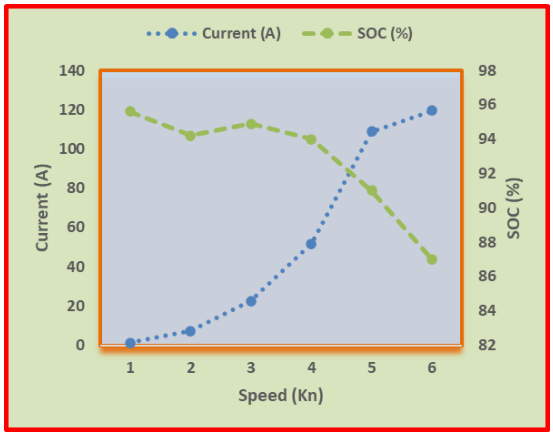


Figure 4 Correlation between boat speed, current, and state of charge (SOC)

Figure 4 shows how the boat speed and the electrical current and the state of charge are related to each other. The horizontal axis represents the boat speed, which ranges from 1 to 6 knots. The left side of the graph is current in amperes. The right side of the graph is state of charge in percentage. When the boat speed increases, the electrical current increases rapidly. At 1 knot, the current is 2 A, but at 6 knots, it increases to 120 A. This means the boat needs higher electrical power when it goes faster. In contrast, when the boat speed increases, the state-of-charge decreases. At 1 knot, the state-of-charge is 96%, but at 6 knots, it decreases to approximately

87%. This implies that the battery will drain faster when the boat moves faster because the current requirement is higher. The state-of-charge decreases slowly until the boat reaches 4 knots. Thereafter, it decreases very rapidly, similar to the large jump in the electrical current. The graph shows that there is a balance between how much the battery lasts and the boat speed. The boat speed, electrical current, and state-of-charge are all interconnected. The graph indicates that caution should be exercised with the current to maintain a high state-of-charge and improve the energy efficiency of boats. The boat speed and state-of-charge are two important factors to be considered while operating electric propulsion boats.

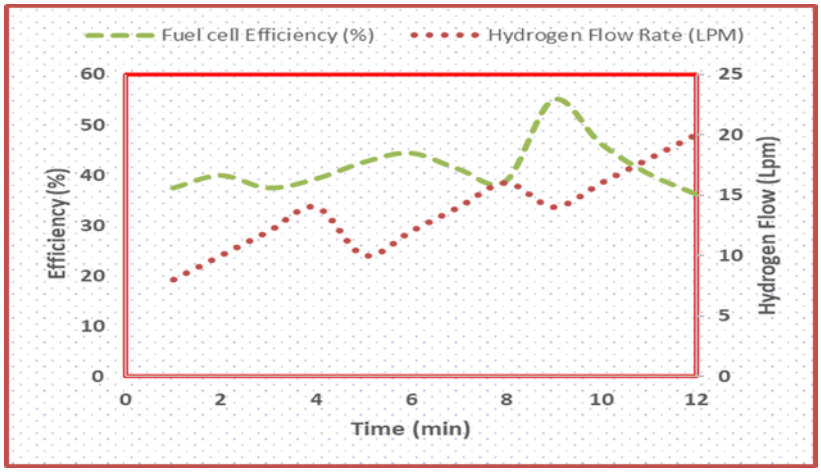


Figure 5. Effect of Hydrogen Flow Rate on Fuel Cell Performance

Hydrogen flow rate effect on the Proton Exchange Membrane Fuel Cell performances was investigated and evaluated in relation to its power generation and efficiency. Experimental studies were carried out in the range of hydrogen flow rates from about 8 Liter pre minute (LPM) to 20 LPM. Figure 5 shows the efficiency change of the fuel cell in terms of hydrogen flow rate. From the results of this experiment, it was shown that the fuel cell performance and power generation were positively affected by increasing hydrogen flow rate. At low hydrogen flows, the performance and efficiency of the fuel cell were moderate. However, with the increase in the hydrogen flow rate, the electrochemical process at the fuel cell becomes more intense, thus producing more electrical power and better performance in terms of the charging process. As a result, at the hydrogen flow rate from 8 to 12 LPM, fuel cell efficiency increased from around 37% to approximately 45%. It should be noted that the increase in the hydrogen flow rate resulted in better hydrogen supply to the fuel cell and anode. It allowed for providing stability in the chemical processes in the fuel cell, thus reducing the problem of fuel starvation. Moreover, a steady hydrogen flow led to better voltage output and increased efficiency in battery charging. The highest efficiency (about 55%) occurred at the hydrogen flow rate of about 14 LPM. This hydrogen supply rate can be considered the optimum one since the fuel cell exhibited the highest stability in terms of voltage output and improvement in charging current efficiency. It can be stated that the regulation of the hydrogen flow is necessary for increasing fuel cell efficiency and ensuring stable charging of the battery. An excessive hydrogen flow rate leads to decreasing efficiency. The results show that hydrogen flows higher than 14 LPM produced the efficiency of less than 40%. It can be explained by increased fuel losses, high charging currents, and heat generation. Excessive hydrogen can be counterproductive since it reduces fuel efficiency because of hydrogen fuel losses.

4. Crew Competency and Training Implications

One of the major outcomes of this project will be the identification of emerging competency requirements associated with hydrogen-powered maritime operations. The transition toward hydrogen-fuelled vessels introduces new operational responsibilities for marine engineers onboard, particularly in relation to hydrogen handling, fuel system monitoring, emergency response, and risk management.

In its latest recommendation, the Maritime Just Transition Task Force (MJTTF) has developed a comprehensive framework for competence development related to hydrogen as marine fuel. The recommended practice categorizes competencies into several thematic areas including: general hydrogen knowledge and risk awareness; hydrogen fuel containment and bunkering systems, fuel supply systems and gas consumers, technical safety barriers and hazardous area management, maintenance procedures, and emergency response and contingency management.

The competency requirements are classified according to four levels of cognition: knowledge, understanding, application, and integration. These levels provide a structured approach for developing training programs capable of preparing maritime personnel for hydrogen-fuelled ship operations. The experimental vessel served as an effective educational platform for developing practical competencies related to hydrogen propulsion systems. During the trial tests, the operators gained hands-on exposure to: compressed hydrogen storage and handling, PEM fuel cell startup and shutdown procedures, battery-fuel cell hybrid energy management, hydrogen leak detection systems, emergency shutdown operations, pressure and temperature monitoring, and operational risk assessment. The project highlighted that hydrogen competency development must extend beyond theoretical instruction and include practical operational training. Human factors play a critical role in maintaining safety during hydrogen operations, particularly in emergency situations where rapid decision-making and procedural compliance are essential.

5 Conclusion

PEM fuel cell propulsion system design was developed and experimentally tested in a 5 kW PEM fuel cell, 48 V LiFePO4 battery pack, and intelligent energy management system in a small boat. The experiments showed stable electric power generation, proper distribution, and efficiency improvements of the hybrid system. In particular, battery technology proved efficient when meeting short-term power needs and the fuel cell worked continuously to ensure sufficient energy. Hydrogen supply rate played a crucial role in the fuel cell's efficiency, and the most appropriate flow rate value was 14 litters per minute. Both battery management system and hydrogen safety technologies provided proper functioning and safety of the experiments. The project also contributed to the development of future skills of seafarers related to ships with hydrogen fuel cells propulsion systems. This study confirms the possibility of creating a practical hybrid propulsion system based on hydrogen technology and prove its role in the decarbonisation and reduction of maritime emissions.

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Analysis of impact of safety parameters on increased safety levels with autonomous ships

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Abstract: The maritime industry is undergoing significant transformation driven by the development and implementation of autonomous vessels. Need for this transition is made because of ecological and economic reasons which came as result of increased ship dimensions. Even if autonomous navigation does not reduce the overall number of maritime accidents, the reduction of onboard personnel exposure inherently contributes to an increase in safety at sea. Increased safety is one of the primary goals for autonomous shipping, although this safety increase has not been quantified in academic literature. Collision avoidance is very significant factor of safety in navigation originally performed by seafarers on board. Seafarers keep a proper lookout, use navigation aids, apply COLREG rules and communicate with other approaching vessels to make an agreement regarding collision avoidance maneuver. These navigational situations are common especially in high traffic areas. This paper presents safety parameters that are essential for the advancement of navigation safety and presents how they can contribute to the improvement of autonomous navigation upgrading them in critical navigation areas (Bolbot V, et al. 2022; Mousazadeh H et al. 2018; Paoletti S. et al. 2023). Furthermore, the authors propose a novel model that correlates defined safety levels with the current stage of development of autonomous ship technologies and navigation systems.

Keywords: safety parameters; autonomous ships; levels of safety; ship collisions

1. Introduction

New systems and technologies are experiencing rapid growth today. Novel systems, such as Maritime Autonomous Surface Ships (MASS), and new initiatives in maritime transport have been introduced (Yara Birkland, 2018; Smart Maritime, 2020), including significant projects in autonomous shipping such as Maritime Unmanned Navigation through Intelligence in Networks (MUNIN), Advanced Autonomous Waterborne Applications (AAWA), and Safer Vessel with Autonomous Navigation (SVAN) (Bolbot et al., 2022). The article also highlights the importance of overcoming regulatory barriers, such as the absence of explicit legal frameworks and the need for new definitions for unmanned ship operations, to ensure the safe and secure adoption of autonomous ships. Ensuring safety in collision avoidance systems within autonomous ships is of high importance, and there is scope for further research and development. Further development regarding the safety of autonomous ships could focus on key topics such as sensor fusion and perception development, collision prediction and collision avoidance algorithms, communication and coordination among all parties involved in autonomous shipping, regulatory frameworks and new standards requirements, human-machine interaction, and simulation and testing. In this article, the authors propose new requirements regarding these

topics and how to address all these aspects in future research. Regarding sensor fusion and the development of perception, the technology will combine data from visual images, environmental sound recordings, Radio Detection and Ranging (RADAR), Light Detection and Ranging (LiDAR), satellite navigation, and vessel transponders. These sensors could be installed, and the data processed using innovative artificial intelligence and machine learning software (Thombre et al. 2022). In this article, the authors propose a list of sensors with their respective weaknesses and strengths, analyse sensor fusion (Österlund et al.), and discuss the development of situational awareness with a collision avoidance proposal mainly related to coastal waters and port approaches. Furthermore, the authors analyse the most common types of sensors potentially used in collision avoidance systems and how collision system will perform.

2. Analysing sensor technology in relation to safety parameters of autonomous ships

Various sensor inputs and outputs present significant challenges in the current development of autonomous ships. In the article, the authors emphasise the importance of such sensor technology in defining the required level of safety and their use in collision avoidance systems.

The most commonly used sensors in sensor fusion for autonomous ships include:

1. **Global Positioning System (GPS)**: GPS provides important information about ship positions, which is essential for navigation and situational awareness in collision avoidance.
2. **RADAR**: RADAR is used for detecting and tracking objects, such as other vessels or buoys, and can provide information on their distance, speed, and direction.
3. **Automatic Identification System (AIS)** used for navigational data exchange and as aid to communication systems
4. **Light Detection and Ranging (LiDAR)**: LiDAR is used to produce 3D maps of the environment, which assists in obstacle detection and collision avoidance.
5. **Sonar**: Sonar is used for detecting underwater objects and can provide information on their distance and size.
6. **Camera**: Cameras provide visual information about the environment, which can be used for object detection and recognition.
7. **Artificial Intelligence (AI) and Machine Learning (ML)**: AI and ML algorithms process and analyse sensor data, enabling the vessel to make decisions based on the information obtained from the sensors.

These sensors are integrated using sensor fusion techniques, such as probabilistic methods (e.g., Kalman filters) or neural network methods (e.g., recurrent neural networks), to produce a more accurate and comprehensive representation of the environment. In the development of autonomous ships, navigation is a key concept for enhancing collision avoidance and for utilising such sensors in collision avoidance systems. The key challenge is to establish priorities and to assess this technology in terms of safety level, as well as to determine which sensor input should have the highest priority for situational awareness in collision avoidance (Burmeister and Constapel 2021). Grading sensor technology can be illustrated as in figure 1 (Mousazadeh et al. 2018).

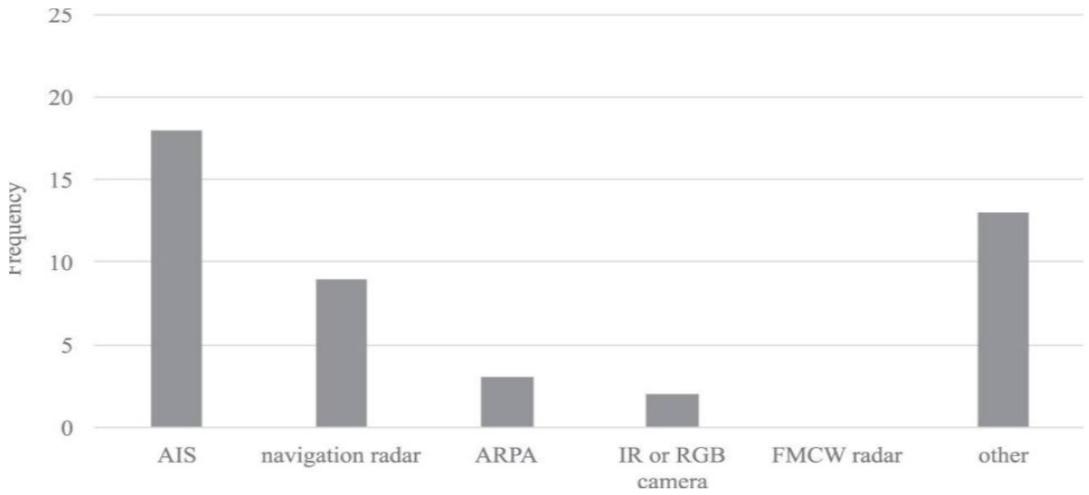


Figure 1. Chart of sensor types for objects and environment.

As per figure 1 is visible that AIS has highest priority level as sensor types with autonomous ships. It presents fundamental sensor and is related to:

1. Collision avoidance of autonomous ships present important part in collision avoidance system of autonomous ships – data from AIS could be integrated with Radar and LiDAR to enhance situational awarness;
2. Communication of autonomous ships with broadcasting informations between autonomous ships enabling ships to exchange informations regarding manouvering intentions as ultimate pirority;
3. Combination of informations from AIS system with other sources can enhance situational awarness of autonomous ships;

Following figure 1 as per priority of sensors on autonomous ships after AIS is Radar, Lidar, cameras and sonars.

2.1 Analyse of sensor fusion on autonomous ships in correlation with safety

Sensor fusion on autonomous ships can be described as the process of combining and integrating data from multiple sensors, such as cameras, radars, LiDAR's, and sonars, to obtain an overview with more precise and exact perception of the environment and surrounding areas. The goal is to bypass the restrictions and limitations of particular sensors and enhance the perception of the autonomous ship (Pietrzykowski et al. 2022).

The process of implementation of sensor fusion with autonomous ships still present significant demand, which is visible through the set of series of challenges such as:

1. Data accuracy - false date due to various restrictions such as sensor failure, weather restrictions, interruptions by other electronic devices can trigger false sensor alarms;
2. Quality of presented pictures - inaccurate size of detected objects such as vessels, navigational marks-buoys, landmasses - this could be enhance by using methodology of optical flow where analyzing the motion of objects and the ship itself to predict potential collisions and adjust course accordingly (Noel et al. 2019);
3. Constraints due to various ranges in detection of objects;
4. Using LiDAR for improved detection of targets and objects, and for path planning of such vessels(Noel et al. 2019)
5. Sensor fusion integration - integrating sensor fusion into the autonomous ship's AI system can be challenging, as it requires sophisticated methods such as probabilistic models for system state estimation and neural networks for data fusion.

An example how the autonomous ships would realize some of sensor fusion technology in figure 2 is given example (Paoletti et al. 2023)

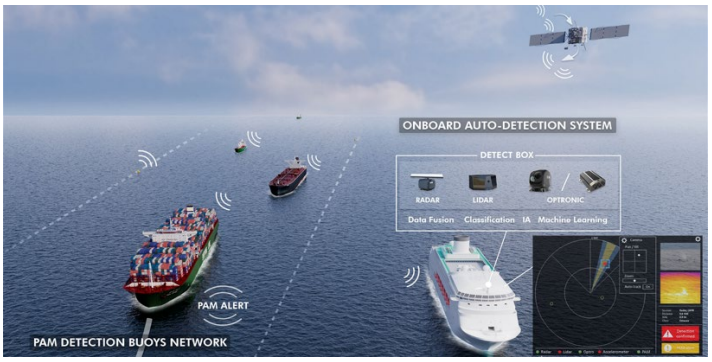


Figure 2. An example of on-board auto detection system.

2.2 Proposed methodology for sensor fusion (collision avoidance) on autonomous ships

When needed to emphasis important sensors for collision avoidance on autonomous ships there are numerous sensors but of high importance for collision avoidance are following:

1. Radar - providing reliable detection of targets, and all relevant parameters related to required data;
2. LiDAR - measuring the time needed for lights which return upon reflecting from objects, also providing 3D maps with surrounding area and providing assistance in detection of the vessels and other objects including navigational aids;
3. Cameras - new type of cameras for autonomous ships enabling to capture visual image with improved possibility for detection, tracking, recognition- also various types of cameras such as visible light cameras, infrared (IR) cameras, thermal cameras, stereo cameras, 360° cameras, hyperspectral cameras, multi-sensor cameras system, high speed cameras etc.
4. AIS - presents an important role in enhancing the safety, efficiency, and interoperability of autonomous ships by providing real-time vessel tracking, identification, and communication capabilities. Within integration of AIS into their onboard systems, autonomous ships can navigate safely and effectively in maritime environments, avoiding collisions and complying with international regulations.
5. GPS – providing geographical location and enabling to autonomous ship to determine ship's position, if GPS failing to give correct position autonomous ships should also use alternative means such as inertial navigation system, dead reckoning, radio navigation system, visual navigation etc. (Rivkin 2021)
6. Sonar – enable autonomous vessel to detect underwater targets with possibility to use two types of sonars such as forward looking sonars and side-scan sonars.
7. VHF – can enhance safety and effectiveness in period transition for communication between autonomous ships and conventional ships. It will ensure safety and interoperability in period while still conventional ships will be active. VHF is handled by hybrid system.

Sensor fusion is important part on autonomous ship where still many parts are in phase of developments and further research studies and projects. Various methods implemented through the scientific articles and projects. There are methods, such as probabilistic methods, which use statistical models to estimate the state of the system, or neural network methods, which use neural networks to learn from the data and fuse them. Neural network method can use a recurrent neural network (RNN), presenting a type of neural network that can process sequential data, to fuse the data from a camera and a radar and generate a collision warning.

The multi-sensor fusion architectures can be classified into three groups based on the level of data abstraction used for fusion. (Farahnakian et al. 2019) Early fusion, also called pixel-level fusion, combines raw data from the sensors before applying any information extraction strategies. Middle fusion, also called feature-level fusion, fuses the extracted features from each raw sensor data and then performs detection on the fused data. Late fusion, also called decision-level fusion, independently performs detection from each sensor and the

outputs of each sensor are fused at the decision level for final detection. (Farahnakian and Kekkonen 2020). As per figure 3 is visible output result after processing input data.

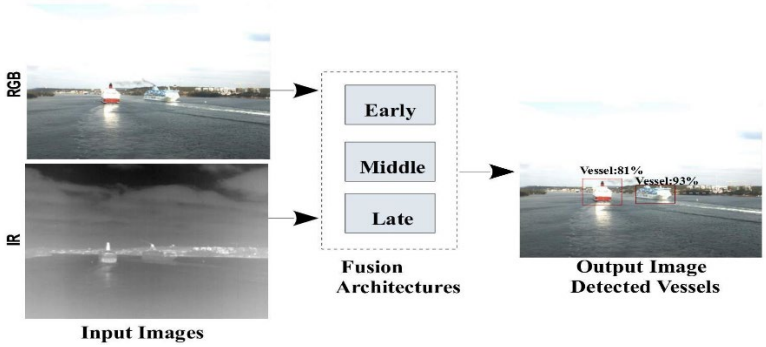


Figure 3. An example of input and output images.

In this article authors presenting correlation between two module sensor fusion module and collision avoidance module. In the first module sensor fusion, there are two groups such as navigation, which depends on input of navigational sensors and reading the charts whit contribution to safety of navigation during passage and second group related to target detection based on input of AIS (Automatic Identification System) and various sensors with priority to sensors for detecting the image and recognition potential collision danger. Based on above further process is recognition of potential collision danger with proposal of safety levels, which will trigger alarm in RCC (Remote Control Centre) where is positioned RCC operator who has to monitor situation and according level alarm with factor. Authors propose factors C_f (collision avoidance factor) in range 1-25 where C_{fg} is range (1-6) lowest alarm in RCC centre, C_{fy} (7-10) medium alarm and C_{fr} (11-25) high alarm with highest attention and high risk of collision. Actuators and system control presents integration with collision avoidance module.

The Collision Avoidance Factor (Cf) is derived from sensor-fusion outputs and is intended to provide an aggregated indication of collision risk. The calculation considers parameters commonly used in maritime collision assessment, including Closest point of approach (CPA), Time to chlosest point of approach (TCPA), relative bearing, bow crossing range (BCR), bow crossing time (BCT), vessel speed and course, traffic density, and COLREG encounter classification. In addition, ship-specific dynamic and technical characteristics, such as stopping distance, turning ability, maneuvering performance, and response time, are incorporated. These parameters are obtained from the navigational sensors previously described. The proposed Cf ranges (low, medium, and high) represent conceptual risk categories intended to support RCC operator awareness and prioritization of collision-avoidance actions. As this paper presents a conceptual framework, detailed weighting, threshold calibration, and validation procedures are left for future research and experimental evaluation.

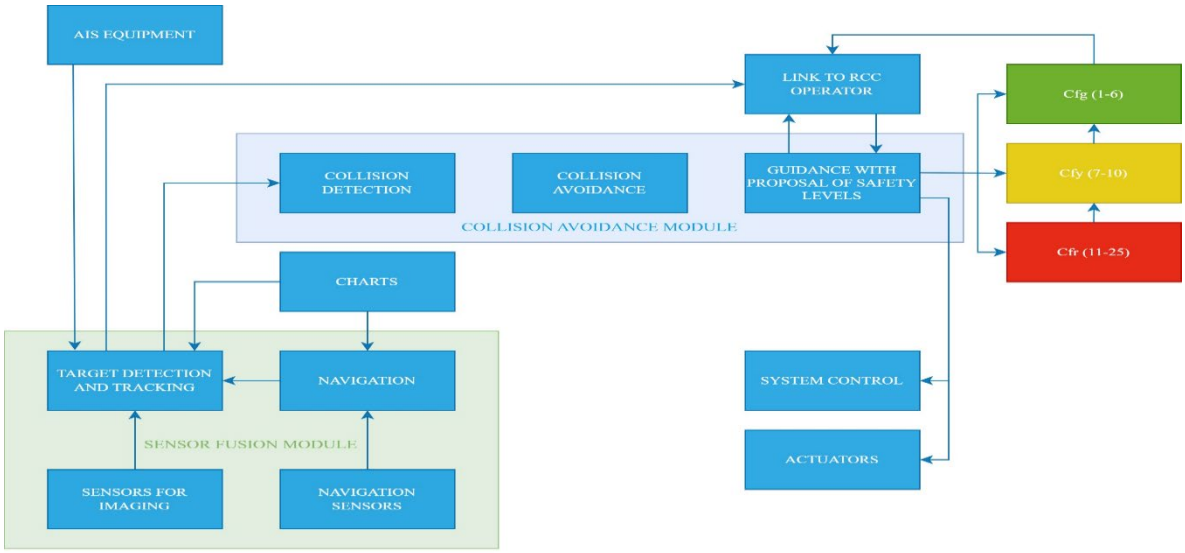


Figure 4. Scheme Model of integration of sensor with collision avoidance model

Proper integration of sensors can assist autonomous ships to overcome barriers and limits of sensors and contribute to enhance perception of various collision avoidance situations. A enhanced model should consider DCPA, TCPA, relative bearing, vessel maneuverability, traffic density, restricted waters, and COLREG obligations. It is also raised concern about maintenance of various sensor systems and autonomous ships must developed enhanced situational awareness for various environmental conditions which additionally might affecting safety of such ships.

There are few more points in regard of sensor fusion, which should be considered in RCC centre and where RCC operator would additionally observe such as:

1. Proper selection and integration of required sensors depending about C_f (collision avoidance factor);
2. Based on C_f factor RCC operator should be able to choose proper sensors depending on required safety level/ raised demand in particular moment;
3. Develop defined protocol based on safety levels;
4. Implement algorithms for situation assessment and risk analysis to evaluate the significance of sensor inputs and make informed decisions under uncertainty.
5. Know how sensor will be integrated with Autonomous navigation system/ and with other systems;

By implementing all given steps RCC centre with RCC operated would perform with maximum safety and efficiency in various situations. VHF communications are managed through cooperation between RCC and STCC operators. The RCC oversees routine communications and vessel monitoring, while STCC operators assume direct control and communication responsibilities during high-risk or safety-critical situations.

3. Conclusion

Integration of various sensors to enhance safety of autonomous ships present important role. This also present a big challenge for researchers how to implement and make these new technologies in maritime shipping reliable and redundant. The main goal is how information from all sensors would present correct surrounding areas and how same enabling decision making in particular situations and how these ships will avoid collision.

As main achievement from sensor technology is how autonomous ships detecting various ships targets, floating/ drifting object, navigational hazard, shallow waters, environmental conditions, conventional ships during period of transition. By fusing all information from various sensors, the sensor fusion system is built to overcome limitations by developing high redundancy on autonomous vessels. As important goal in this article is fusion between sensor module and collision module with integration to RCC centre. Furthermore as big challenge is flow of data between RCC centre and important data from these two modules. Ongoing research

in these field and new innovations presenting safety and reliability of autonomous navigation systems at sea for further development of autonomous ships.

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The Role of the Consolidator and the Specifics of Consolidating LCL Cargo Flows

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Abstract: In the context of the growing importance of LCL transport within global supply chains, the study focuses on analysing the consolidation process and the role of the consolidator in the logistics and distribution of groupage containers. Alongside the theoretical framework, the issue is examined through a practical case study of a consolidator's operations. The aim of the paper is to analyse the consolidator's role as a Third-Party Logistics (3PL) operator in rationalizing and optimizing LCL flows. The scientific contribution of this research lies in evaluating the consolidator's role in optimizing containerized cargo flows and in identifying the key elements and drivers of effective LCL shipment management. The findings may serve as a basis for further research and for improving logistics processes in international containerized trade.

Keywords: LCL - Less than Container Load; consolidators, Third-Party Logistics (3PL).

1. Introduction

Less than Container Load - LCL is an increasingly prevalent logistics model in international trade, as the consolidation of smaller consignments from multiple shippers into a single container rationalizes costs and enhances supply chain flexibility. By integrating maritime, rail, and road transport within a unified supply and logistics system, containerized transport enables the efficient organization of cargo flows, particularly on routes spanning multiple countries and transport modes.

In contrast to conventional Full Container Load (FCL) carriage, LCL movements are characterized by more complex logistics processes and multiple consolidation and deconsolidation stages. In this context, consolidators - acting as Third-Party Logistics (3PL) operators - play a pivotal role in coordinating both physical and procedural activities, including transport, warehousing, and documentation.

Accordingly, the core research problem addressed in this paper concerns the analysis of consolidation specificities and the role of the consolidator within LCL container cargo flows, with the aim of identifying key factors and challenges in the organization and distribution of LCL consignments.

The objective of the study is to provide deeper insight into the consolidator's impact on LCL logistics efficiency and to open possibilities for future research on the rights, liabilities, and interactions of consolidators with other stakeholders in international trade.

2. Overview of the prior research

The scientific literature addressing LCL transport and its specific operational characteristics remains relatively limited. As a result, relevant research is mainly found in adjacent fields, including container loading optimization, cargo consolidation models, and the role of logistics service providers in the organization of freight transport.

A significant body of research focuses on the container loading problem as a three-dimensional combinatorial optimization task. Studies such as those by Bortfeldt and Wäscher (2013) emphasize practical constraints such as container-related limitations, handling unit characteristics, shipment indivisibility (all handling units within a single order typically must be shipped together, without split shipments), positioning

constraints inside the container, even load distribution, and achieving in-container stability. Similarly, Moura and Oliveira (2025) propose algorithmic approaches to improve stowage efficiency. Jamrus and Chien (2016) point out that literature on container loading optimization is relatively extensive, while their work focuses on more complex less than container loading problem. They analyse the challenges, i.e. limitations consolidators face when stuffing containers and, to enhance profitability, propose a hybrid genetic algorithm for optimizing the arrangement of multiple consignments within a single container.

Jugović (2020) analyses the economic impact of the container loading problem, emphasizing the importance of maximizing container capacity utilization, as inefficient use of space reduces transport efficiency and increases per-unit cargo costs. In this context, achieving maximum utilization of available container capacity in international trade represents a continuous challenge for logistics planning, as the problem of optimally loading a large number of smaller cargo units into a single container remains complex and does not have a unique solution.

Qin et al. (2014) analyse consolidation and container loading models aimed at improving space utilization and lowering transport costs, while emphasizing the increasingly important role of third-party logistics providers (3PL) who collect shipments, consolidate them into containers of different sizes and costs, and ship them via various routes to destination ports. Similarly, Hanbazazah et al. (2019) study the cargo consolidation problem from the perspective of a logistics service provider who collects shipments from multiple suppliers, performs cross-docking, and consolidates them at intermediate hub facilities before delivery to a single customer, with the goal of forming full container loads while minimizing unit transport costs and meeting agreed delivery time windows.

Bertazzi, Moezi, and Maggioni (2021) examine whether combining full container loads (FCL), less than container load (LCL) shipments, and air freight within a Vendor-Managed Inventory (VMI) system can reduce total transport and inventory costs. Their model shows that integrating different delivery modes can yield significant savings compared to using a single mode, while also clarifying when it is optimal to rely on only one of the aforementioned transport options.

Mostafa and Eldebaiky (2023) investigate sustainable consolidation in a two-echelon logistics system and compare a model incorporating LCL shipment consolidation through distribution centers with a direct shipment model from origin to destination. Their results show that consolidation can significantly improve system efficiency, reduce transportation costs by more than 40%, and lower environmental impact. Although the model is applied to a relatively simple network, the authors highlight its potential extension to more complex systems, such as the international liner shipping industry, where LCL consolidation may provide additional benefits.

According to Beškovnik (2023), transporting small shipments is becoming an increasingly important way of operating global supply chains. In his research, he investigates sustainable parameters of intermodal and overseas transport of small consignments, indicating that proper consolidation and organization of LCL flows can increase utilization of transport capacity and significantly reduce environmental pollution.

Dhanush and Sulthana (2025) analyse LCL consolidation processes and FCL transportation with an emphasis on the role of Customs House Agent (CHA) procedures. According to these authors, LCL service performance depends on optimizing warehousing–customs procedures and expediting customs clearance, thereby reducing delays at consolidation centers.

Overall, the reviewed literature confirms the topical relevance of the subject and the complexity of cargo consolidation and container optimization problems, while also revealing a clear research gap regarding the consolidator's role as a key coordinating actor in the efficient organization and optimization of LCL cargo flows.

3. The Role of the Consolidator in LCL Transport Optimization

Considering the importance of all participants in the LCL logistics chain (importers and exporters, ocean carriers, inland carriers, customs, ports, warehouses, and others), freight forwarders, consolidators, shipping agents, and other "third-party logistics" (3PL) entities play a key role - both physically and documentarily - in optimizing groupage container transport. This section analyses in detail the legal position and operational role of the consolidator as a 3PL operator in the execution and optimization of LCL transport.

3.1. Legal position of the consolidator in LCL transport

LCL transport is a complex logistics system in which, alongside numerous actors such as ocean carriers, customs terminals and warehouses, customs authorities, road and rail carriers, freight forwarders, importers and exporters, inspection services, and others, consolidators of LCL consignments also play a significant role.

The international rules governing the issue of carrier liability for cargo damage do not provide a definition of a consolidator. It could not have been expected that the International Convention for the Unification of Certain Rules of Law relating to Bills of Lading (Hague Rules) and Hague–Visby Rules would address the legal status of a consolidator, as they were adopted prior to the development of containerized cargo transport (Comité Maritime International, 2018). United Nations Convention on the Carriage of the Goods by Sea (Hamburg Rules) likewise do not recognize the concept of a consolidator, but they distinguish between the contractual carrier and the actual carrier (United Nations Commission on International Trade Law, 1978). By analysing the activities performed by a consolidator and its role in the realization of maritime transport, it can be concluded that the consolidator appears in the role of a contractual carrier, while the liner shipping company acts as the actual carrier. Therefore, all rules governing the legal position of the contractual carrier will be relevant in assessing the rights and obligations of the consolidator. In fact, the contractual carrier represents a Non-Vessel Operating Common Carrier (NVOCC).

When analysing the role of a consolidator, it is also necessary to take into consideration the UN Convention on Contracts for the International Carriage of Goods Wholly or Partly by Sea (Rotterdam Rules). They represent a modern set of rules that regulate not only the issue of carrier liability for cargo damage, but maritime transport as a whole. However, it is important to emphasize that they have not entered into force and therefore do not constitute a binding legal source. The Rotterdam Rules likewise do not specify the consolidator as one of the persons who may appear in the carriage relationship; instead, they define the concepts of a performing party and a maritime performing party. According to the definition of a performing party, a consolidator may be a contractual carrier, but it cannot be a performing party unless it physically performs the carriage (United Nations Commission on International Trade Law, 2008).

In LCL shipments, the consolidator has a dual legal position. It acts as a contractual carrier (NVOCC) in relation to the individual shippers, and as a shipper in relation to the actual carrier (shipping line).

Consolidators generally do not perform the entire door-to-door transport themselves, instead, they act as contractual carriers, organizing and coordinating the movement of goods between the Place of Receipt and the Place of Delivery. In practice, they play a central role in arranging carriage by combining individual consignments into consolidated shipments. For the cargo they receive, they issue a House Bill of Lading (HBL) to each shipper, confirming receipt and contractual responsibility for the goods. They then obtain a Master Bill of Lading (MBL) from the actual carrier, under which they are typically listed as the shipper. This dual-document structure reflects their role as intermediaries between shippers and ocean carriers in containerised transport operations. It is also common in practice for forwarders to instruct a consolidator to arrange value-added services within the transport–logistics chain, for example import customs clearance, final delivery to the consignee, etc. In this way, consolidators go beyond the narrow function of consolidating LCL shipments and act as coordinators of all or part of the logistics and transport process.

3.2. Operational role of the consolidator in LCL transport

While the above illustrates that the consolidator and the freight forwarder are distinct parties collaborating toward the same objective - moving the shipment (container) to the Place of Delivery - it is important to mention that the forwarder may formally assume the role of consolidator in practice. The prerequisite is registration as an NVOCC, i.e., a carrier that does not operate vessels but organizes and sells ocean freight as an intermediary between the shipper and the ocean carrier. In that capacity, the forwarder is authorized to issue a House Bill of Lading (HBL), which serves as the receipt for the goods and describes the individual shipment within the larger consolidated consignment.

Consolidation work undertaken by forwarders is demanding, because the likelihood that sufficient cargo will be available on a given route to fully load an entire container with groupage cargo is low. Forwarders therefore tend to consolidate only in special cases, for example when a client simultaneously has sufficient cargo from two or more different suppliers using the same port of loading. In that case, the forwarder arranges for all the cargo to be collected either at a partner’s warehouse or at one of the suppliers, who then loads the

complete cargo into the container. Such cases are rare, and when forwarders receive a consolidation inquiry, they often decline due to the high coordination effort and low margin, preferring to hand the job to specialist consolidators focused on this line of business.

For groupage container transport to be arranged, there must be demand - i.e., a person or company ordering goods from an overseas supplier. Depending on quantity and needs, the consignee opts either for an FCL booking or for LCL groupage for smaller volumes.

By entrusting their logistics operations to specialized 3PL providers, businesses can redirect their resources toward core competencies such as product development, marketing strategies, and customer relationship management. (Krishnakumar, 2025, p. 1030)

3PL providers integrate logistics services, warehousing, and ancillary operations to meet the needs of principals or end users - by consolidating consignments from multiple suppliers, temporarily storing those consignments, and initiating delivery or further dispatch (Mostafa and Eldebaiky, 2023, p. 3). To deliver cost-effective and efficient services and thereby gain competitive advantage, 3PL firms are generally compelled to optimize their handling and cross-dock costs through effective consolidation (Hanbazazah et al., 2019, p. 188). This approach fosters low-cost, time-efficient distribution systems; however, due to the complexity of the required arrangements and coordination, optimization models are needed to organize and manage the distribution network.

According to research by Northeastern University and Accenture, the services most frequently outsourced to 3PL operators include direct transportation services (67%), customs brokerage (58%), freight bill payment/audit (54%), transportation management (46%), warehouse management (46%), and shipment consolidation (42%). Consolidation is thus entrusted in a significant share (42%) to specialized consolidation companies, which represent a key segment of logistics services (Lieb and Bentz, 2005, p. 8). In line with these findings, consolidation of consignments - outsourced in 42% of cases to specialist consolidators - constitutes an important logistics function. As specialized providers within the LCL domain, consolidators typically perform the following activities:

- collecting cargo from different buyers and suppliers at the warehouse – container freight station (CFS);
- sorting and labeling cargo for onward dispatch by destination;
- load planning and consolidation to optimize container space utilization;
- arranging and controlling transport and customs documentation;
- tendering the stuffed container to the ocean carrier at the port of loading;
- releasing the cargo to the destination consolidator (agent) at the port of discharge, who then organizes stripping and final delivery to the buyer.

LCL consolidation process is designed to provide a cost-effective and flexible solution for international seaborne movement of smaller quantities. Potential inefficiencies can stem from paper documentation requirements, lack of digital integration, procedural redundancies, and weak coordination among stakeholders, including shippers, customs, and port authorities. Such operational bottlenecks can lead to shipment delays, prolonged customs processing times, higher costs, and reduced visibility across the logistics chain. (Dhanush and Sulthana, 2025, p. 530). These challenges degrade overall service quality, reduce customer satisfaction, and limit the competitiveness of logistics service providers

Once the groupage cargo is stuffed, the consolidator delivers the container to the load port and tenders it to the ocean carrier for the sea leg. Upon loading, the carrier must issue a Bill of Lading - an instrument acknowledging receipt of the goods for carriage. Beyond being a receipt, the Bill of Lading serves as written evidence of the contract of carriage and as a document of title symbolizing the goods described therein. Under the Bill of Lading, the carrier undertakes to transport the goods in the quantity, condition, and on the terms stated, and to deliver them at destination to the lawful holder. As a transport document, it contains the description of the cargo by marks, kind (name), quantity, and apparent condition according to the shipper’s written declaration (Pomorski leksikon, 1990).

In the case of an LCL shipment, once the container is on board, the carrier issues the consolidator a Master Bill of Lading (MBL), naming the origin consolidator as shipper and the destination consolidator as consignee for all cargo in the container.

As an NVOCC, the consolidator must issue a Bill of Lading (HBL - House Bill of Lading) to each shipper for each shipment loaded into the container. This is a bill of lading issued by the freight forwarder to the shipper. It is used when the forwarder organizes the movement from the actual shipper to the ultimate consignee, often as part of LCL groupage or where the forwarder acts as intermediary between the shipper and the ocean carrier. The HBL accompanies the shipment along the transport leg managed by the forwarder but relies on the Master Bill of Lading (MBL) as the underlying document issued by the carrier. Thus, in LCL carriage, multiple HBLs (for multiple individual consignments within the groupage container) can be linked to a single MBL covering the whole container.

Depending on the shipper's instructions, either original bills of lading may be issued, in which case the consignee must present an original bill of lading to obtain delivery, or a sea waybill may be issued, in which case the cargo is released to the consignee immediately without the need to present an original document. (Maersk, 2023) In cases where original bills of lading have been issued and surrendered or otherwise accounted for, cargo may be released at the destination under a telex release instruction issued by the carrier or its agent. In LCL practice, HBLs are typically multimodal, since in addition to the ocean leg they also cover inland pre - carriage to the port of loading and inland on-carriage from the port of discharge to the destination CFS. A multimodal bill of lading evidences carriage by at least two different modes under the responsibility of a single transport operator (in this case, the LCL consolidator).

After the container is discharged at the port of discharge, the destination consolidator/agent withdraws the full (groupage) container from the terminal and drays it to its bonded warehouse (CFS), where the container is stripped. Cargo is palletized as needed so it can be dispatched by road to the final delivery points, at which the consolidator must place the cargo at the disposal of the consignee named on the bill of lading. The consignee may take delivery from the warehouse upon presentation of the original bills of lading received from the supplier (where originals are in circulation) or upon issuance of an electronic release.

By choosing LCL, each transport principal sharing container space with other shippers and consignees pays ocean freight based on the volume occupied by the shipment within the container. The cost of LCL shipping depends on several factors, primarily the volume of space the cargo occupies, its weight, and the shipping route. (Maersk, no date).

The NVOCC's objective is to utilize at least 80% of the selected container's volume for the move to be economical. Freight is rated on a weight/measurement (W/M) basis - i.e., by weight (in tonnes) or by measurement (in cubic meters), charging whichever yields the higher payable amount (Beškovnik, 2023, p. 82).

In practice, LCL freight is almost always rated on measurement (by cubic meter), as truly heavy shipments where the weight factor exceeds the measurement factor are rare. Often, for heavier cargo, consolidators apply a weight surcharge, which is likewise calculated per cubic meter. The minimum freight payable by the end customer to the consolidator is the charge for one cubic meter of cargo (or one metric tonne), even if a smaller quantity is shipped. On lanes with thinner cargo flows, the consolidator may set a higher minimum - two or three cubic meters (or tonnes).

3.3. Core characteristics of consolidator operations

Consolidators are companies that often originated as logistics service providers - for example, shipping agencies handling routine FCL carriage - and over time evolved into groupage operators and common carriers in the maritime sector, serving a network of destinations.

Beyond their own branch offices across a given region, consolidators' operations depend on a broad set of supply chain stakeholders who, in effect, function as business partners: warehouse operators (public and private), inland carriers, ocean carriers (liners), agents, and freight forwarders worldwide. Thus, a consolidator may have offices in Europe while transacting daily with the foregoing actors and with numerous other consolidators. Representative examples globally include China NVOCC Container Lines Ltd., Netrise Logistic Co. Ltd., World Jaguar Logistics Inc., Troy Container Line Ltd., Shipco Transport, Lavinstar America Inc., Vanguard Logistic Services Inc., Sinotrans Ltd., and others.

In global trade conditions, a strategy of opening offices at key locations worldwide and across Europe is a prerequisite for delivering reliable services to clients, with a continual focus on innovation and adapting to market needs.

Within Central and Eastern Europe (CEE), only a handful of consolidators specialize in organizing LCL container transport, such as Shipco Transport d.o.o., World Transport Overseas d.o.o., ECU Worldwide GmbH, Ostara Group d.o.o., with Boxline UCL d.o.o. among the market leaders in this European segment. By way of example, on import flows for the CEE market, consolidators route cargo to final destinations so that, after discharge from the vessel, containers are drayed to the consolidator's central CFS in Slovenia. Each container arriving at Koper is planned for optimal space utilization at origin, with shipments from multiple shippers for different consignees across Europe (Slovenia, Croatia, Austria, Poland, Czechia, Romania, Bulgaria, Serbia, Bosnia and Herzegovina, North Macedonia, Albania, Montenegro, Kosovo, …). At the central CFS in Slovenia, the container is stripped and cargo is placed into a closed (non-public) warehouse, sorted, photographed if needed, palletized and stretch-wrapped, measured, inspected with a condition report if any damage is observed, and appropriately labelled, after which it is dispatched by road to the final destination named on the bill of lading, where it is tendered to the buyer at the agreed place of delivery. In addition to groupage cargo arriving in containers, smaller lots also arrive by groupage trucks from other deconsolidation hubs where the cargo has already been stripped (Milan, Hamburg, Rotterdam, and Vienna or Budapest for containers railed from Asia).

Alongside hub-handling via the central CFS, where market volumes to a particular destination warrant it, consolidators also dispatch full consolidation containers directly to final destinations per the bills of lading - i.e., to destination CFS facilities such as Belgrade, Budapest, Zagreb, and Prague. This reduces warehouse handling costs (no intermediate stripping at the Slovenian hub) and correspondingly lowers the risk of cargo damage due to additional handling.

4. Case example of organizing LCL container transport with emphasis on consolidator activities

Selecting optimal LCL cargo routings is critical for both the consolidator and the users of this mode. By minimizing transport and handling costs, the consolidator improves market competitiveness and creates more room to achieve margin per unit carried. Throughout the transport planning and execution, the consolidator must safeguard client satisfaction and loyalty by offering competitive freight rates, regular and reliable services, and competitive transit times - factors that directly influence future cooperation, volume, and profit.

Consolidators work with their agents and partner consolidators worldwide and are particularly focused on origin markets that generate the largest flows (for Europe, chiefly Asian countries such as China, Hong Kong, Singapore, India, Korea, and Vietnam).

For example, origin agents at Asian load ports stuff groupage cargo into containers consigned to the Port of Koper as the discharge port. For each LCL container tendered to the carrier, the carrier's Master Bill of Lading (MBL) shows the loading agent (consolidator) as shipper and the discharging agent (deconsolidator) as consignee. Thus, upon arrival, the carrier releases the entire container to the consignee named on the MBL - the deconsolidator. For every individual shipment, the loading agents issue an HBL (House Bill of Lading) to the cargo owner, naming the consolidator as the destination agent. Once the carrier's release is received, the consolidator arranges pickup of the full groupage containers from the terminal (raising customs transit documents as required) and drays them to its closed CFS/bonded warehouse, where stripping is performed.

At the central CFS, cargo arriving in groupage containers is sorted and properly labelled; where necessary, a damage report is drawn up and the cargo is photographed. To maximize cube utilization and minimize unit transport cost, cargo is typically loaded into containers unpalletized at origin; palletization is then performed at the destination warehouse to simplify, accelerate, and reduce the cost of onward handling. Operations teams use an integrated system to monitor the sequence and speed of stripping, and on that basis order trucks for onward dispatch from the central warehouse to the delivery destinations shown on the bills of lading. For each destination, a truck is ordered that will be loaded exclusively with cargo for that country (e.g., Croatia, Serbia, Austria, Czechia, etc.). The higher the loaded volume/weight, the lower the road cost per unit. The objective is to load as much groupage cargo as practicable onto each semi-trailer. A Dispatch Manifest is prepared for the truckload and onward movement, combining shipments that are ready to move so as to maximize both cube and weight. Smaller lots are nevertheless often loaded - for example, where part of the cargo is non-stackable; where

dangerous goods cannot be top-stowed or bottom-stowed with other cargo; or where special packages will not permit cargo to be stowed on or under them due to size, weight, or shape. After loading the truck, a customs transit document (T1) is issued. To prepare the transit file, each shipment must be accompanied, at dispatch, by the requisite documents: a copy of the bill of lading, the commercial invoice and/or pro forma invoice, the CMR consignment note (Convention on the Contract for the International Carriage of Goods by Road), and where applicable the packing list and the Material Safety Data Sheet (MSDS).

The transit document debits the consolidator's customs bond/guarantee, typically equal to 30% of the total value of the goods under transit. By lodging the transit declaration and security, the applicant becomes the "principal" in the transit procedure. After the goods are placed under transit, the principal must present the goods intact (with seals unbroken, as applicable), together with the transit declaration, to the office of destination within the prescribed time limit (European Commission, 2021, p. 41). Clients are then notified that their shipment has departed by truck from the Slovenian CFS and of the expected time the goods will be positioned at the delivery place named on the bill of lading. Upon arrival of the truck at the destination warehouse and customs office, the driver presents the transit papers to customs; the T1 is discharged; customs authorize unloading and storage; and, if there is damage, a warehouse damage report is prepared and the cargo photographed. Once the cargo is placed into storage, the consolidator, acting as destination agent, must issue to each client, for each of that client's shipments on the truck, a Delivery Order / Release Order - the document releasing the cargo to the consignee, confirming availability and enabling the consignee to lodge the import customs declaration and take delivery from the warehouse. Release will be granted provided a Telex release or Seaway bill is in force, or original bills of lading have been given to the consolidator, and all applicable transport charges have been settled. If any charges remain unpaid and no credit terms exist, or if originals are in circulation and have not been submitted, the consolidator will place a hold on the shipment.

5. Conclusion

To assess the role and importance of consolidators in the rationalization and optimization of LCL flows, the research highlights their core function as third-party logistics (3PL) operators coordinating a wide range of activities - from cargo collection, warehousing, and consolidation, through to deconsolidation and cargo distribution. Based on the conducted research, the authors conclude that relevant international regulations on liability for cargo damage (Hague and Hague-Visby Rules, Hamburg Rules, Rotterdam Rules) do not provide a definition of a consolidator. Nevertheless, their provisions relating to the shipper and the contracting carrier will be applicable to the consolidator depending on their position in each particular transport arrangement. The consolidator serves as a link between different shippers who have opted for LCL shipment and the actual carrier. By issuing a House Bill of Lading, the consolidator assumes the legal status of a contractual carrier (NVOCC) and, accordingly, is liable for any loss or damage to the cargo while the it is in his custody. In relation to the actual carrier, the consolidator will be regarded as the shipper and, as such, will be declared in the Master Bill of Lading. It is important to emphasize that a consolidator should be distinguished from a freight forwarder, although a freight forwarder may also act as a consolidator.

The study also identifies the situations in which shipment consolidation delivers the greatest benefits, as well as numerous challenges associated with coordination requirements and the overall process complexity of consolidating LCL container shipments.

Using a practical example of organizing LCL container transport through consolidator activities, the theoretical framework is implemented within a real transport operating environment. Special attention is devoted to the specifics of logistics and documentary management, management of transport documents, and distribution optimization via centralized warehouses and local destination services, providing valuable insight into day-to-day challenges and solutions in LCL logistics.

In conclusion, the study confirms that consolidators, as specialized 3PL operators, play a decisive role in optimizing LCL flows, reducing transport costs, and increasing competitiveness in the LCL container shipping market. Their activities and consistent management of a complex logistics chain constitute a critical success factor in LCL flows as a distinct segment of international trade.

The research results identify specific operational and documentary activities for LCL shipments based on consolidator business practice and may serve as a basis for further research aimed at improving logistics

processes and the legal and operational aspects of the roles and interactions of all stakeholders in the LCL container supply chain. A particular contribution of the study is the emphasis on the role, activities, and importance of consolidators within both the physical and document flows of LCL container transport logistics.

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Expert-Based Assessment of Grounding Risk in Coastal Route Selection

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Abstract: In the modern maritime industry, ship grounding remains one of the most serious safety risks, particularly in navigationally constrained areas and zones of dense traffic. This paper investigates the decision-making process in route selection while accounting for grounding risk through an expert-based assessment involving experienced masters and deck officers. Participants evaluated and ranked alternative routes differing in distance from shore, navigational complexity, spatial limitations, exposure to navigational hazards, and voyage duration, with particular emphasis placed on grounding risk assessment. The research results provide empirical support for risk-based navigation planning and contribute to the validation of quantitative grounding risk models in coastal navigation. The paper also highlights the importance of integrating professional judgement into decision-support systems aimed at improving maritime safety.

Keywords: grounding risk, expert-based assessment, route selection, maritime safety

1. Introduction

Coastal navigation represents one of the most complex areas of maritime navigation, as it takes place in a space where numerous risk factors are simultaneously present, such as proximity to the coast, shoals, confined passages, variable currents, and increased traffic density. Unlike ocean navigation, where the manoeuvring space is greater, in coastal areas, route selection directly affects vessel safety and the probability of grounding (Zec, 1997; Simović, 2001). Voyage planning under such conditions is not only an operational task, but also a fundamental safety obligation. In practice, route selection always involves a compromise between shorter voyage time and a safer, often longer route (Jašić, Belamarić and Trošić, 2011). This relationship between safety and efficiency is particularly important in coastal navigation, where an incorrect assessment may have serious consequences. Previous research on maritime navigational risk has mainly focused on quantitative grounding risk assessment, AIS-based traffic analysis in restricted waters, and risk-based route planning approaches. Recent studies have addressed grounding risk quantification in channel waters using AIS data, quantitative safety assessment in coastal waters, and risk-based path planning for collision and grounding prevention (Yang et al., 2023; Maidana et al., 2023; Zhang et al., 2025). In the literature, grounding risk has long been recognised as an important segment of maritime safety, and various analytical, statistical, and operational models for assessing grounding risk and grounding frequency have been developed (Galić et al., 2022). Previous studies also show that grounding assessment and prediction models have been developed through a range of different approaches, from review and chronological analyses to more recent risk assessment models for coastal waters (Galić, 2025). However, fewer studies have directly examined how experienced seafarers evaluate grounding risk in coastal route selection under multi-factor navigational conditions (Hänninen et al., 2014). In this respect, the present study contributes by linking expert judgement, route-choice preferences, and AIS-supported observations within a coastal navigation context. This paper presents the results of a survey conducted among experienced masters and deck officers with the aim of determining how professionals assess grounding risk when selecting a coastal route. Particular emphasis is placed on the effects of distance from shore, width limitations of the fairway, sea currents, navigational hazards, and voyage duration. The obtained results provide an empirical basis for understanding the decision-making process in coastal navigation and serve as a foundation for the validation of quantitative grounding risk assessment models.

2. Grounding Risk Factors in Coastal Navigation

Safe navigation in coastal areas requires detailed route planning prior to departure. Such planning must take into account not only the voyage length, but also the overall spatial and operational conditions within which the vessel is navigating. In coastal navigation, grounding risk is most strongly associated with the spatial complexity of the navigational area, proximity to the shore, and limited manoeuvring space (Zec, 1997; Ministry of the Sea, Transport and Infrastructure of the Republic of Croatia, 2014). The factors affecting route safety assessment can be divided into external and internal factors. External factors include bathymetry, shoals, rocks, coastal obstacles, traffic density, meteorological and oceanographic conditions, sea currents, and width restrictions in passages and straits. Internal factors relate to the vessel's draught, manoeuvring characteristics, the technical condition of onboard equipment, and crew competence (Radulić, 2001; Kos, Vranić and Zorović, 2010). Compared with ocean routes, coastal navigation offers several possible route alternatives, but at the same time increases the need for more precise decision-making. A route that is shorter and more favourable in terms of voyage time is not necessarily the safest if it passes closer to the shore, through a narrower passage, or through an area affected by stronger sea currents. In such cases, route selection must be based primarily on safety criteria (Jašić, Belamarić and Trošić, 2011; Simović, 2001). Local traffic patterns are also of particular importance. In archipelagic and channel areas, vessels often navigate through spatially restricted sectors, where additional risk is created by other vessels, fishing traffic, yachts, local ports, and marinas. Under such conditions, it is not sufficient to consider only the geometry of the route, but also its practical navigational safety (Ministry of the Sea, Transport and Infrastructure of the Republic of Croatia, 2014). It follows that grounding risk assessment in coastal navigation must include multiple factors simultaneously. For this reason, the expert-based method was applied in this study in order to examine how professional seafarers prioritise individual safety-related factors when selecting a route in real navigational situations.

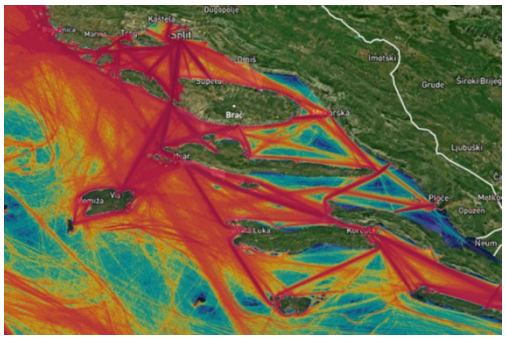


Figure 1. Traffic density in a section of the eastern Adriatic coast (Source: MarineTraffic).

3. Research Methodology

3.1. Aim of the survey

The aim of the survey was to gain insight into the way experienced seafarers assess grounding risk and make decisions when selecting a coastal navigation route. In particular, the study sought to determine to what extent respondents take into account distance from the shore, the presence of navigational hazards, width restrictions, the influence of sea currents, and voyage duration. The survey also served as an empirical test of the assumption that seafarers in coastal waters tend to favour a safety optimum, that is, a route representing a balance between acceptable voyage time and reduced grounding risk. The methodological framework of the research is based on the general principles of scientific research and survey-based data collection (Vujević, 1983; Zelenika, 2000). The use of expert judgement in maritime safety is particularly valuable in situations involving complex operational conditions and multi-criteria safety choices that cannot be adequately described by a single quantitative parameter alone (Hänninen et al., 2014).

3.2. Sample and data collection

A total of 100 professional seafarers of Croatian nationality participated in the survey, including 72 deck officers and 28 masters serving on ships over 500 BRT. In terms of seagoing experience, 13% of respondents had between 1 and 5 years of experience, 39% between 5 and 10 years, and 48% more than 10 years. The data

were collected over a one-year period, both in person and electronically. In-person completion of the questionnaire took place in the presence of the author, while electronic completion was intended for respondents who were on board ships or away from their place of residence at the time of the survey. Throughout the process, respondents were guaranteed anonymity. This approach enabled the collection of responses from a professionally relevant and experienced group of participants.

Table 1. Structure of respondents by rank and seagoing experience.

What is your rank on board ships over 500 BRT?	Number:	Percentage:
Deck officer	72	72%
Master	28	28%
TOTAL RESPONDENTS	100	
How long have you been serving on ships over 500 BRT?	Number:	Percentage:
1 to 5 years	13	13%
5 to 10 years	39	39%
More than 10 years	48	48%
TOTAL RESPONDENTS	100	

3.3. Structure of the questionnaire

The questionnaire consisted of 14 questions structured to cover the key aspects of grounding risk assessment in coastal navigation. The questions referred to the basic characteristics and experience of the respondents, the relationship between voyage time and safety level, the method of obstacle avoidance in coastal and open waters, route selection with regard to distance from shore and vessel size, the assessment of the probability and consequences of grounding, and the ranking of routes according to a group of safety-related factors. The results were analysed both collectively and separately for deck officers and masters in order to determine whether differences existed between the two groups. In this way, it was possible to assess whether there is a common professional decision-making pattern with regard to safety in coastal navigation.

4. Results of the Expert-Based Assessment

4.1. General safety attitude in route choice

When asked how often they would choose a route not recommended in the sailing directions if such a route were shorter and easier, most respondents demonstrated a cautious approach. Overall, 36% of respondents stated that they would never choose such a route, 33% said rarely, 27% said sometimes, and only 4% said always. These results indicate that professional seafarers, regardless of rank, generally adhere to recommended routes and do not show a pronounced tendency to choose risky alternatives for the sake of saving time.

4.2. Safety versus voyage duration

When choosing among several routes of different lengths and levels of risk, the vast majority of respondents chose the safer, but not the longest, route. In the scenario with four alternative routes, Route 1, being the shortest and most dangerous, was not selected at all; Route 2, which was short but still risky, received only a negligible share of responses; while Route 3 received 67% of responses and Route 4 received 32%. This shows that respondents do not choose either the shortest route or automatically the longest route, but rather seek a safety optimum between voyage duration and risk level. A similar pattern was confirmed in later questions involving routes at different distances from the shore. In the case of a vessel 100 m in length with a draught of 5 m, respondents predominantly selected the route at a distance of 4 NM from the shore, which offered a reasonable time saving while still maintaining a sufficient safety margin. For a larger vessel of 250 m in length and 11 m draught, the preference shifted further towards routes more distant from the shore, thus confirming that vessel dimensions and draught directly influence the assessment of a safe route.

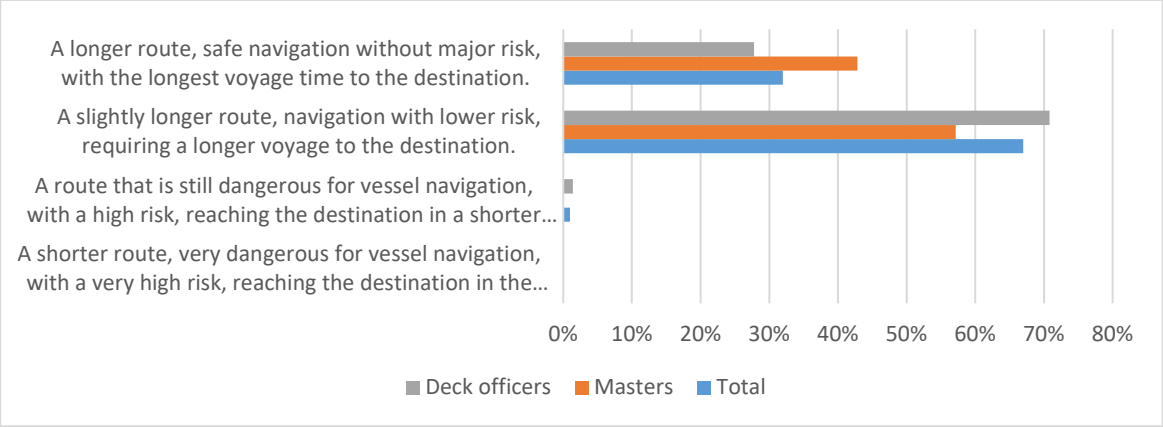


Figure 2. Comparison of route choices according to route length, arrival time, and hazard level.

4.3. Manoeuvring behaviour in coastal and open waters

A significant difference was observed between respondents' behaviour in coastal waters and in the open sea. When avoiding obstacles in coastal waters, 84% of respondents used manual steering, while only 16% used autopilot under continuous supervision. Among masters, this relationship was even more pronounced: 96% used manual steering, and only 4% used autopilot under supervision.

By contrast, in the open sea, 89% of respondents used autopilot under supervision, while only 11% used manual steering. These results clearly show that professional seafarers perceive coastal waters as substantially more demanding and riskier, and therefore prefer direct human control of the vessel under such conditions.

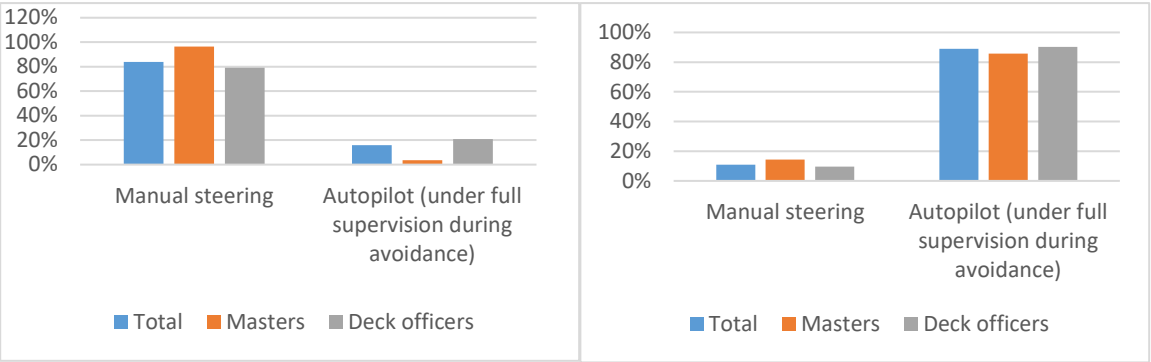


Figure 3. Comparison of obstacle-avoidance methods in coastal and open waters.

4.4. Effect of ship size and distance from shore

In scenarios where respondents selected a route with regard to vessel size, draught, and distance from the shore, a clear relationship was confirmed between safety assessment and the route's distance from the shore. For the smaller vessel, most respondents selected intermediate-distance routes representing a compromise between safety and efficiency, whereas for the larger vessel there was a more pronounced preference for routes farther from the shore.

Additional confirmation was provided by AIS data collected from the MarineTraffic platform for the Greek archipelago, where actual routes of merchant vessels and their reported draught were analysed. Using the selected sample, the author compared the closest point of passage from the shore or shoal with the vessel's reported draught. This behavioural pattern is consistent with the survey results and further confirms that, in practice, vessel draught is perceived as an important factor in assessing the safety margin from the shore. In this

respect, AIS-based approaches provide a useful empirical basis for analysing navigational behaviour in restricted waters (Huang et al., 2019).

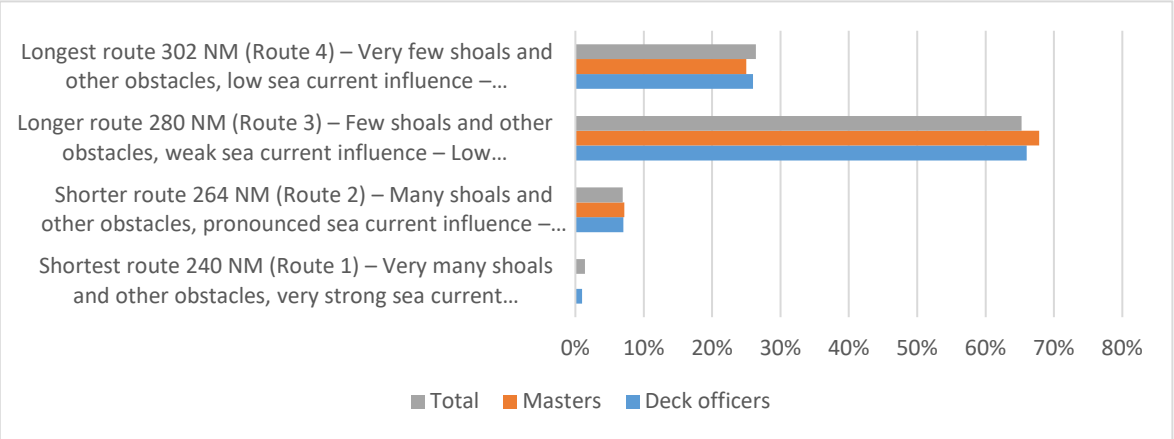


Figure 4. Comparison of the overall route selection results according to shoals, obstacles, and the influence of sea currents.

4.5. Ranking routes by safety-related factors

In this part of the survey, each respondent assessed seven selection factors for each of the four routes. The scoring was carried out on a scale from 1 to 4, where a higher score indicated a more favourable, that is, safer assessment of the route with respect to the observed factor. Since 100 respondents participated in the survey, the maximum number of points for one factor and one route was 400, while the maximum total number of points per route, considering all seven factors, was 2800. For this reason, the table presents the total summed scores of all respondents rather than individual ratings.

Table 2. Overall ranking of routes according to selection factors.

	POINTS (TOTAL)			
SELECTION FACTORS	1.	2.	3.	4.
Marking of the fairway	305	246	274	286
Influence of proximity to the shore and navigational hazards	270	173	272	326
Width restrictions (passages, straits)	283	167	260	324
Length of the route along the coast	264	207	284	310
Influence of sea currents on navigation	257	182	269	300
Availability of shelter and easier access to assistance in the event of a grounding accident	293	289	267	234
Number of other ports along the route, higher traffic, greater accident probability, greater caution required	247	220	267	318
TOTAL SCORE PER ROUTE	1919	1484	1893	2098

One of the key parts of the survey concerned the ranking of four routes within the Greek archipelagic area according to seven selection factors: marking of the fairway, influence of proximity to the shore and navigational hazards, width restrictions of the fairway, length of the route along the coast, influence of sea currents, availability of shelter and assistance, number of other ports and expected traffic. The overall results showed that Route 4 achieved the highest total score (2098) and was therefore identified as the safest route, whereas Route 2 received the lowest total score (1484) and was assessed as the least favourable. Route 2 consistently received lower ratings due to its greater proximity to the shore, more pronounced width restrictions, stronger influence of sea currents, and a higher number of ports and associated traffic along the route. The obtained results show that respondents do not assess route safety on the basis of a single factor, but rather on the overall relationship between multiple elements. A safer route is therefore not simply the one farther from

the shore, but the one that simultaneously offers lower spatial complexity, better visibility, fewer restrictions, and less exposure to external risks.

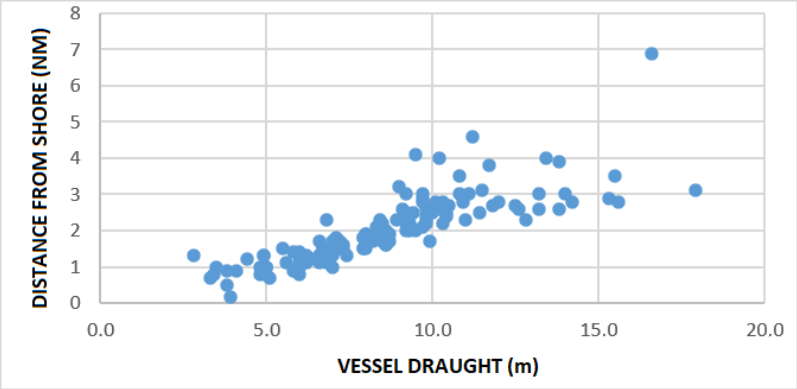


Figure 5. Relationship between vessel draught and the closest distance from shore based on AIS-observed routes in the Greek archipelago.

4.6. Final route preference

In the final question, respondents were asked to select one of the four proposed routes shown in Figure 6 for a larger merchant vessel navigating through the Greek archipelagic area, while simultaneously taking into account a safe distance from the shore, acceptable voyage duration, and the lowest probability of grounding.



Figure 6. Four proposed routes in the final route selection scenario based on safe distance from the shore and voyage time.

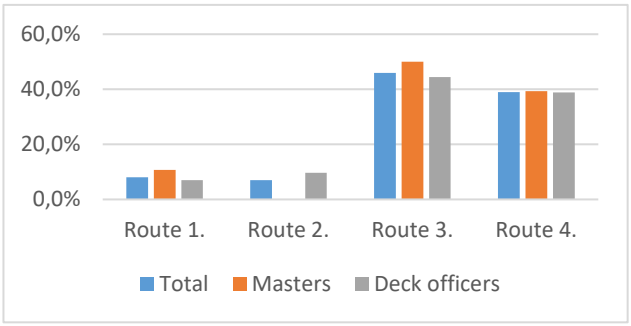


Figure 7. Final comparison of route selection with regard to safe distance from the shore and voyage time.

The overall results showed that Route 3 received 46% of the votes, while Route 4 received 39%, whereas Routes 1 and 2 remained only marginally represented (Figure 7). These results further confirm the previously observed pattern: respondents are not willing to sacrifice safety for a minor saving in voyage time, but neither do they automatically choose the longest route if another route offers a sufficiently high level of safety with a more acceptable voyage duration.

5. Discussion

The obtained results show that professional seafarers in coastal navigation assess grounding risk in a manner that is both consistent and operationally logical. Safety is generally prioritised over time savings; however, respondents do not automatically choose the longest route, but rather the route that represents the best balance between safety and voyage duration. Such an approach is consistent with the fundamental principles of voyage planning and navigation safety assessment (Zec, 1997; Jašić, Belamarić and Trošić, 2011). A particularly important finding is that no significant differences were identified between masters and deck officers in their basic safety attitudes. This points to a relatively uniform professional practice and a shared understanding of the factors that increase grounding risk. Such consistency is important because it shows that safety assessment is not based solely on individual intuition, but also on professionally adopted patterns of judgement.

In addition, the results confirm that vessel size and draught have a direct influence on route selection. The larger the vessel and the greater the draught, the greater the required safety margin from the shore. In this sense, the survey does not merely provide a description of respondents' opinions, but also offers an empirical basis for modelling the relationship between vessel characteristics and the desirable distance from the shore (Radulić, 2001; Kos, Vranić and Zorović, 2010). Furthermore, an additional value of the research lies in the fact that the survey results are consistent with observations derived from AIS data and with the general logic of route planning in coastal navigation. The obtained results complement existing quantitative and AIS-based studies of navigational risk by showing how professional seafarers, in real operational conditions, assess the safety optimum between route length, distance from the shore, and perceived grounding risk. The value of this study lies in the fact that it treats the professional judgement of seafarers not merely as a description of operational practice, but also as an empirical basis for understanding route selection criteria in coastal navigation. This study is based on the professional judgement of Croatian seafarers supported by AIS observations in selected navigational contexts. While the results provide a meaningful empirical basis for understanding coastal route selection, future research should expand the sample to a broader international population and combine expert-based assessment with simulation-based validation, human reliability assessment, and digital decision-support models (Blindheim et al., 2023; Brandsæter and Madsen, 2024).

6. Conclusion

The expert-based study showed that professional seafarers, when selecting a coastal route, prioritise safety over the minimum route length, while at the same time seeking a route that represents a reasonable compromise between safety and voyage duration. In all analysed scenarios, routes passing closer to the shore, through narrower areas, or through sectors with a higher number of navigational hazards were assessed less favourably and selected less frequently. The survey results also show that manual steering is preferred in coastal waters when avoiding obstacles, whereas in the open sea autopilot under continuous supervision is used much more frequently. This confirms that seafarers clearly distinguish between the safety requirements of these two navigational environments. A particularly important finding is that larger vessels and greater draught lead to a preference for routes at greater distances from the shore, confirming that the safety margin in route selection changes depending on vessel characteristics. The ranking of routes according to multiple factors further showed that professional seafarers assess safety in a multi-criteria manner, rather than on the basis of a single variable. In conclusion, the results of this study provide an empirical basis for understanding the route selection process in coastal navigation and represent a valuable contribution to the validation of grounding risk assessment models and to the development of decision-support systems in maritime safety.

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POSEIDON

Precise Oceanic Structure Engagement with Intelligent Diagnostics and Operational Networking

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Abstract: The maritime industry faces a critical dilemma for underwater inspections: risk human divers or rely on massive, expensive industrial ROVs. To address this, an ultra-low-cost, Artificial Intelligence (AI)-driven underwater vehicle was designed and developed for real-time diagnostics. The proposed prototype, Precise Oceanic Structure Engagement with Intelligent Diagnostics and Operational Networking (POSEIDON), integrates hardware and software into a unified edge-computing system. Built on a modular 3D-printed frame, POSEIDON features a novel vector-thrusting propulsion system. Utilizing custom tilt servos and reliable silicone-neoprene seals, it achieves full maneuverability while eliminating the bulk and expense of traditional vertical thrusters. Complex data is processed entirely at the edge via three AI frameworks: visual mapping for sonar-free navigation, computer vision for immediate detection of structural damage and biofouling, and multi-sensor fusion for predicting invisible chemical leaks. Physical versatility is maximized by a responsive mechanical manipulator with interchangeable attachments, enabling seamless transitions from biological sampling to structural maintenance. By combining multi-layered AI with an innovative mechanical design, POSEIDON offers a highly capable, safer alternative for subsea operations, establishing a scalable foundation for autonomous underwater intervention.

Keywords: AI-integrated Robotics; Underwater Inspection; Biofouling Classification; Smart Maintenance; Affordable Marine Technology.

1. Introduction

The maintenance and inspection of global maritime infrastructure currently rely on two difficult extremes: risking human lives through hazardous manual diving or spending exorbitant amounts on heavy-duty, industrial-class Remotely Operated Vehicles (ROVs). As the maritime industry rapidly shifts toward sustainable and digitized operations, the lack of an affordable, intelligent middle ground has become a critical bottleneck.

Traditional maritime inspections rely heavily on industrial-class Remotely Operated Vehicles (ROVs) that demand massive logistical footprints and specialized support vessels. The existing capital-intensive systems are prohibitively expensive, frequently exceeding hundreds of thousands of dollars in baseline acquisition and daily operational costs (Dalhatu et al., 2023). Conversely, the existing affordable commercial micro-ROVs lack the computational power for active edge-based artificial intelligence, reducing them to passive video-streaming tools. They also severely lack the physical modularity required for interchangeable mechanical manipulators, making active subsea intervention impossible without upgrading to heavy-duty platforms. Furthermore, these intermediate systems fail to integrate real-time sensor fusion for detecting invisible chemical leaks or onboard computer vision for proactively identifying structural damage and biofouling. To bridge this critical gap and transform passive observation into active intervention, POSEIDON is introduced: an ultra-low-cost, 3D-printed, vector-thrusting underwater vehicle engineered as a unified edge-computing system to democratize advanced subsea diagnostics.

2. Literature Review

2.1. Existing ROV Technologies

The current landscape of underwater inspection is dominated by two extremes. On one end are industrial-class Remotely Operated Vehicles (ROVs). While highly capable, these systems are capital-intensive, require specialized operational vessels, and demand massive logistical footprints for deployment and maintenance (Capocci et al., 2017). On the other end are commercial micro-ROVs, which offer affordability but typically lack the computational power required for real-time, onboard diagnostics, reducing them to mere passive video-streaming devices. Furthermore, their closed, proprietary architectures severely limit physical modularity, making it incredibly difficult to upgrade them with interchangeable mechanical attachments or advanced sensor suites. Consequently, a significant portion of intermediate underwater maintenance still relies on manual human diving. This reliance introduces severe safety risks and operational inefficiencies, particularly in hazardous or unpredictable maritime environments.

2.2. Rationale for developing POSEIDON

The development of POSEIDON was driven by the critical need to bridge this gap between prohibitive industrial systems and high-risk human intervention. As the maritime sector moves toward digital integration and sustainability, there is a distinct demand for accessible, intelligent platforms capable of active diagnostics. POSEIDON was engineered to decentralize underwater data processing by utilizing a multi-layered edge AI architecture. By integrating computer vision for damage detection and sensor-fusion for chemical leak identification directly onto the vehicle, the system eliminates the latency of post-mission analysis. Furthermore, its modular, 3D-printed design was specifically developed to bypass the high manufacturing costs that typically bottleneck advanced robotics research.

3. System Design and Architecture

3.1. Body and Structural Design

POSEIDON's structural framework is specifically designed (Figure 1) to prioritize hydrodynamic efficiency, high modularity, and rapid manufacturing. To strictly manage project costs while guaranteeing the vehicle withstands intense underwater hydrostatic pressure, the primary chassis is constructed entirely from 3D-printed PETG and PVC (Kiss-Nagy et al., 2024). Unlike the massive, unchangeable frames of traditional industrial ROVs, this highly modular PETG design allows for immediate physical upgrades, easy part replacements in the field, and the quick addition of new tools, such as our interchangeable mechanical manipulator arm. The physical shape of the hull uses an open-frame layout. This allows ocean water to flow freely over the external sensors and propulsion motors, which significantly reduces drag when the vehicle moves through the water. Furthermore, the frame is carefully balanced to keep the center of gravity as low as possible while providing a large, secure housing for the internal electronics and battery packs. This careful weight distribution ensures the ROV remains highly stable and resists tipping or rolling. This passive stability is absolutely essential for capturing clear diagnostic video, recording accurate acoustic data, and operating the mechanical arm smoothly in unpredictable marine environments.

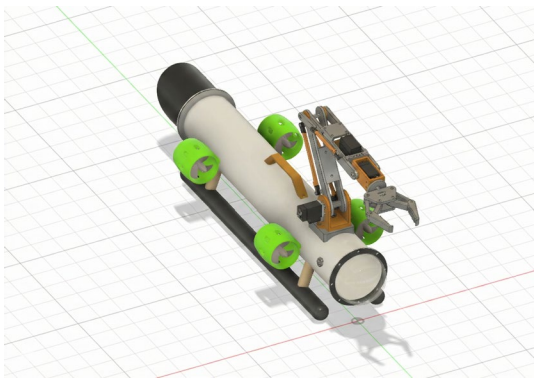


Figure 1. 3D Model of POSEIDON With Robotic Arm for underwater hull/structure maintenance.

3.2. Thruster Configuration and Vector Thrusting

Propulsion and maneuverability are achieved through a unique vector-thrusting system(Figure 3), which replaces the standard, bulky multi-thruster setups. The main pushing power comes from high-torque Brushless DC (BLDC) motors, fitted with custom-designed propellers and housings (Figure 2) to provide maximum thrust efficiently. Instead of relying on several heavy vertical thrusters to steer the vehicle, POSEIDON uses a custom tilt-servo mechanism that physically angles the main thrusters. This tilt mechanism is significantly smaller and much less costly to produce than adding multiple static thrusters, yet it still gives the ROV full six-degree-of-freedom (6-DOF) movement while saving battery life. To ensure these moving parts survive high underwater pressure, the tilt servos are protected using a highly effective neoprene and silicone seal method. This specific sealing technique guarantees that the constant, dynamic movement of the tilt mechanisms does not allow any water to leak inside the motor housing. By keeping the electronics completely dry, this system allows the ROV to steer reliably, maintain precise positioning, and execute complex maneuvers during extended underwater diagnostic operations.

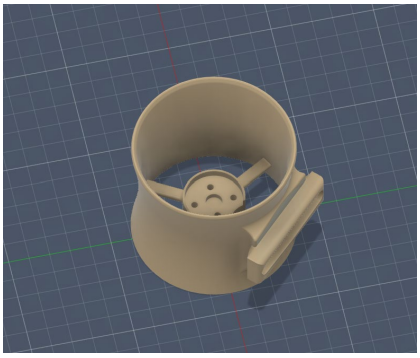


Figure 2. CAD Model of the Thruster POD

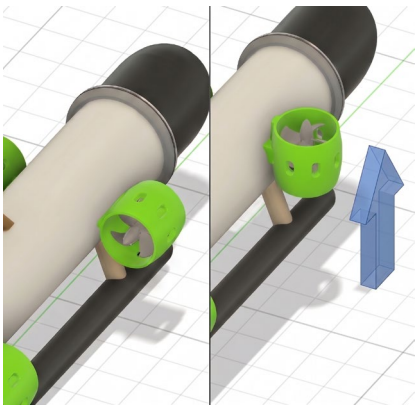


Figure 3. Thruster Tilt visualized

3.3. Buoyancy Control

To maintain the perfect depth without constantly draining battery power through the thrusters, POSEIDON features an active, vented ballast tank system. This variable buoyancy control allows the ROV to easily make itself heavier or lighter, which is a critical feature for hovering in place during long structural inspections. The system relies on a single, high-efficiency gear pump to actively pump ambient water in and out of the internal ballast chambers. During the ballasting process—when the ROV needs to dive—the incoming water pushes the trapped air out of the tanks through a very small, 0.4 mm 'snorkel' vent located at the top. This prevents destabilizing air pockets from forming inside. During the de-ballasting process, when the gear pump pushes water back out to make the ROV lighter, a small amount of surrounding water might naturally try to enter through this same snorkel. However, because the snorkel opening is only 0.4 mm, the water enters at an incredibly low rate compared to the powerful output of the gear pump. This ensures that much more water is pushed out than comes in, allowing the ROV to rise efficiently and smoothly.

3.4. Electrical and Electronics

The computational brain of the POSEIDON platform is powered by a Raspberry Pi 5 microcomputer paired with a custom AI Hardware Attached on Top (HAT) module. This powerful combination allows the ROV to process heavy artificial intelligence tasks directly onboard, without waiting for surface computers. To fully understand its underwater environment, the vehicle is equipped with a comprehensive suite of diagnostic sensors. These include specialized tools for measuring water turbidity, electrical conductivity, and pH levels. It also utilizes an Inertial Measurement Unit (IMU) for spatial balancing, a hydrophone for capturing ambient acoustic data, a water pressure sensor to monitor depth, and internal sensors to detect any accidental water ingress. Crucially, all of these environmental sensors are in direct contact with the actively running AI algorithms, allowing the system to continuously analyze the data and make intelligent decisions in real-time. To support these energy-demanding sensors, AI processors, and drive motors, the system uses a localized power architecture. It is powered by a high-capacity 10,000 mAh 3S lithium-polymer battery pack. Custom-designed Power Distribution Boards (PDBs) safely regulate this energy, ensuring stable voltage is delivered across all critical electronic subsystems.

3.5. Control System

The communication and control architecture of POSEIDON is designed to handle massive amounts of data without the heavy drag of traditional industrial tethers. The vehicle operates remotely using a lightweight, high-speed Ethernet cable as its primary umbilical connection. This streamlined cable allows for fast, two-way communication between the onboard computers and the operator's surface laptop. Unlike older systems that might use simple switches, POSEIDON's precise vector-thrusting servos and drive motors are fully controlled by the operator using intuitive joysticks. When the operator moves the joysticks, these control signals are processed by the surface computer, sent rapidly down the Ethernet cable, and directly received by the Raspberry Pi 5 to execute the physical movement. This direct communication line ensures that the mechanical driving controls remain highly responsive and completely separate from the heavy computational load of the AI video processing. All of the vital telemetry, including the real-time sensor data, AI diagnostic alerts, and live, high-definition video streams, are transmitted back up the Ethernet umbilical and displayed on a custom Graphical User Interface (GUI) (Figure 4), ensuring the operator maintains complete situational awareness at all times.

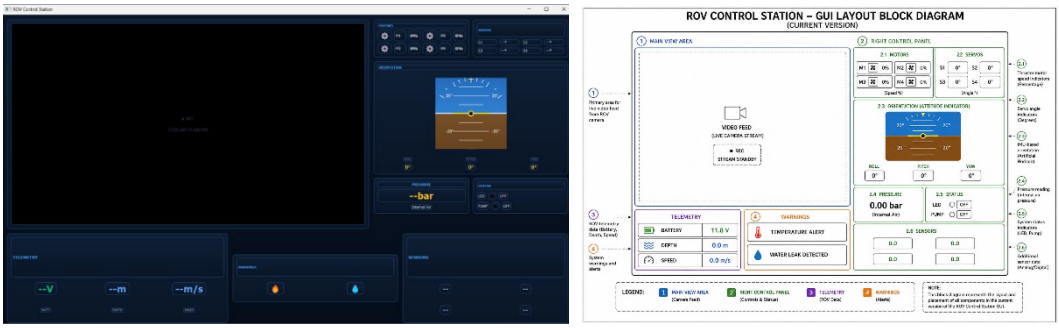


Figure 4. GUI For POSEIDON Operations

4. Multi-Layered Edge AI Diagnostic Framework

To elevate POSEIDON into an active diagnostic platform, it integrates a multi-layered Artificial Intelligence (AI) framework operating entirely at the edge. This decentralized computing eliminates reliance on high-bandwidth topside processing, enabling real-time environmental analysis. The architecture uses custom computer vision models to immediately detect biofouling and structural degradation, actively addressing common underwater imaging challenges (Sugunapriya and Markkandan, 2025). Concurrently, by adapting established sensor-fusion methodologies for low-power edge environments (Sang and Norris, 2023), a specialized onboard algorithm continuously monitors the water column to predict and locate invisible chemical leaks. Finally, a foundational visual mapping system establishes the spatial awareness necessary for the platform's future transition to fully autonomous underwater navigation.

4.1 Overview of the Intelligent Inspection System

4.1.1 Overview

Underwater ROV inspection is often hindered by low visibility and suspended particles. To address this, we propose an intelligent vision system using a Convolutional Neural Network (CNN) to automate real-time detection of biofouling and structural dents, significantly enhancing operator efficiency.

4.1.2 Dataset

A 118-image dataset was utilized. To compensate for this limited size and prevent overfitting, transfer learning was employed. By utilizing a pre-trained backbone, the model effectively extracted foundational visual features without requiring a massive initial dataset. Furthermore, images were resized to 128×128 pixels, normalized, and actively augmented to simulate dynamic underwater conditions (Figure 5). Future real-world trials will systematically expand this dataset.

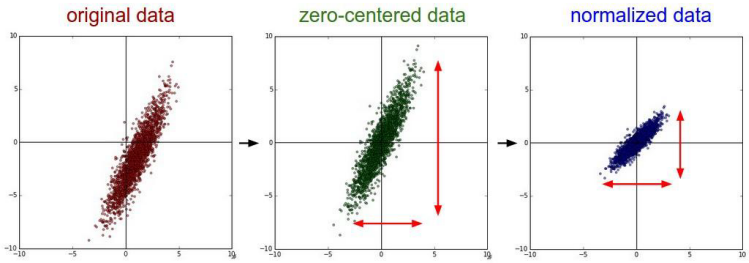


Figure 5. Examples of dataset preprocessing and augmentation

4.1.3 CNN Architecture

The proposed Sequential CNN (Figure 6) extracts feature progressively. Initial layers detect basic edges and colours, while deeper layers identify complex biofouling textures and dent-related distortions. Max pooling layers reduce dimensionality and suppress noise, followed by fully connected layers utilizing a 0.5 dropout to prevent overfitting.

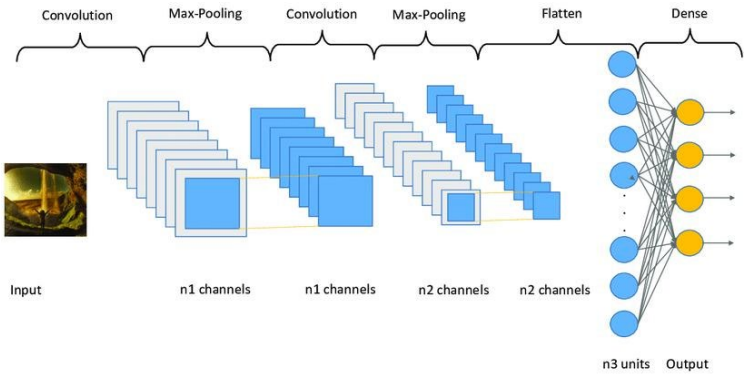


Figure 6. Architecture of the proposed Convolutional Neural Network (CNN).

4.1.4 Learning Process and Optimization

The model is trained using Binary Cross-Entropy (BCE) loss and the Adam optimizer for stable convergence. A sigmoid activation function outputs probabilities, classifying anomalies (biofouling or structural defects) using a 0.5 threshold.

4.1.5 Dual Detection Strategy

A single multi-task model efficiently identifies both biological anomalies (via texture/colour variations) and structural dents (via geometric features and shadows), reducing overall system complexity.

4.1.6 Real-Time Integration and Visualization

Integrated via OpenCV, the system processes 30 FPS ROV video in just 15–20 milliseconds per frame. Real-time detections and prediction confidence scores are displayed as visual overlays on the live feed.

4.1.7 System Output Visualization (Proposed Model Result) (Figure 7)

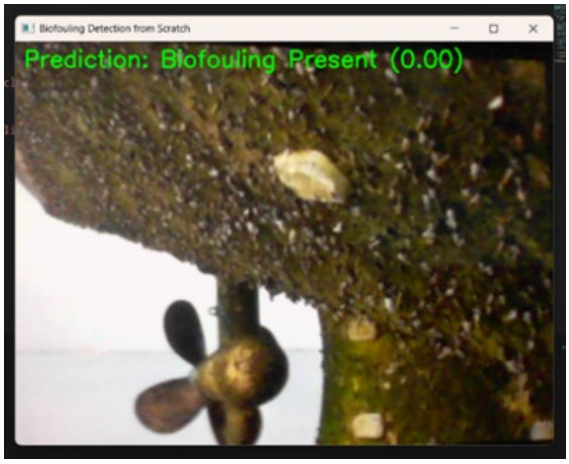


Figure 7. biofouling is detected and displayed along with the prediction confidence in real time.

4.1.8 Summary

By combining robust preprocessing with an optimized CNN, this methodology enables highly reliable, automated marine inspection despite limited initial training data.

4.2 AI Integration for Chemical Detection and Water Quality Analysis

4.2.1 Overview

While visual inspections detect physical degradation, holistic diagnostics require underlying chemical monitoring. We integrated a heuristic, AI-driven module tracking pH, conductivity, and turbidity to act as an early-warning system, predicting invisible chemical anomalies in real-time alongside optical data.

4.2.2 Multi-Sensor Data Acquisition

The system captures a comprehensive water profile using a localized sensor suite: pH (acidity/alkalinity levels), conductivity (concentration of dissolved ions), and turbidity (suspended physical particulates). Aggregated, these distinct metrics formulate a robust physical and chemical diagnostic profile.

4.2.3 Predictive Model for Water Quality Classification

Replacing fragile chemical analysers, we deploy a computationally lightweight, rule-based algorithmic model optimized for embedded systems. This pattern-recognition approach instantly classifies the aggregated data into five distinct environmental "fingerprints":

- Baseline / Normal: All metrics within safe parameters.
- Physical Contamination: Spikes in turbidity with stable chemistry (e.g., suspended soil).
- Acidic Discharge: Sharp pH drops, high conductivity, clear water (e.g., chemical spill).
- Alkaline Wastewater: High pH, conductivity, and turbidity (e.g., agricultural runoff).
- Environmental Dilution: Low conductivity, neutral pH (e.g., rainwater influx).

4.2.4 Real-Time Telemetry and Operator Interface

The predictive model processes telemetry continuously, feeding results into a custom Python graphical dashboard. The interface translates raw numerical data into color-coded severity alerts, enabling operators to seamlessly monitor the chemical state alongside live camera feeds.

4.2.5 System Validation

The software pipeline and interface (Figure 8) were rigorously validated using simulated data streams. This confirmed the logic of the algorithmic thresholds and ensured low-latency conversion of raw inputs into real-time, actionable insights.

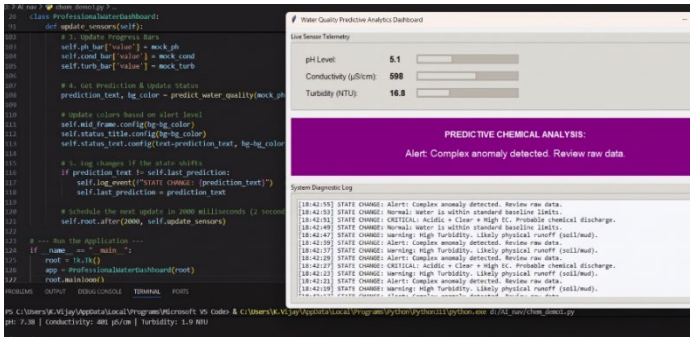


Figure 8. GUI for Chemical Composition Prediction

4.2.6 Summary

To transition from simulated data, future real-world testing plans outline controlled tank trials and port deployments, ensuring scalable, holistic chemical monitoring without complex laboratory equipment.

4.3 Ai-Based Navigation through Monocular Visual Odometry

4.3.1 Overview

To eliminate reliance on expensive LiDAR or acoustic sonar, POSEIDON utilizes a lightweight Monocular Visual Odometry (VO) module. Using a standard RGB camera, the system estimates the ROV's trajectory by analysing geometric shifts between consecutive image frames, drastically reducing hardware costs.

4.3.2 Feature Extraction and Motion Estimation

The engine employs the ORB algorithm to detect and track environmental landmarks in real-time via a Brute-Force Matcher. Erroneous matches caused by suspended particles or lighting shifts are filtered using RANSAC. By calculating the Affine Transformation between matched points, the system derives relative translation and rotation, enabling accurate positioning without external GPS.

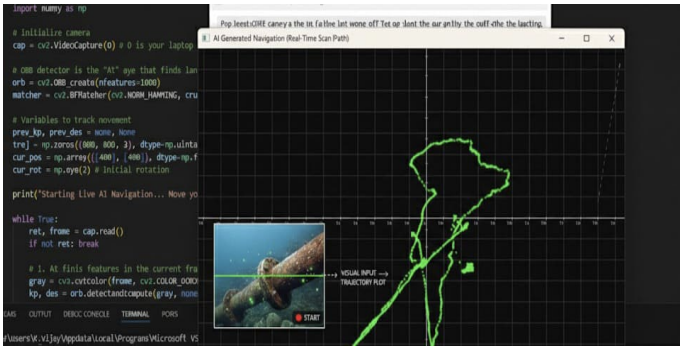


Figure 9. Real time visual plotting

4.3.3 Real-Time Path Plotting

Motion vectors are continuously integrated to reconstruct the vehicle's trajectory. A dual-window dashboard displays a live camera feed overlaid with tracked feature points, alongside a coordinate grid mapping the ROV's physical "breadcrumb" path relative to its starting point. (Figure 9)

4.3.4 Conclusion and Future Work

This camera-only framework successfully establishes low-cost localization via dead reckoning. Future developments will integrate Monocular Depth Estimation to recover metric scale and Loop Closure techniques, transitioning the system into a complete Visual SLAM architecture.

5. Conclusion

The POSEIDON project demonstrates that marine inspection no longer requires massive capital investments or the routine endangerment of human divers. By successfully combining 3D-printed modularity with localized edge AI, this research proves that highly capable, real-time diagnostic systems can be built affordably. The value of this platform extends far beyond simply cutting daily operational costs; it makes proactive subsea maintenance accessible to a much wider range of operators. Furthermore, by digitizing underwater structural and environmental data, POSEIDON directly supports the connected ecosystems of smart ports and serves as a vital subsea inspection companion for emerging Maritime Autonomous Surface Ships (MASS). Ultimately, by delivering an open architecture that can already navigate, detect structural damage, and predict chemical leaks on its own, POSEIDON provides a practical stepping stone toward a future of fully autonomous underwater intervention.

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Human Factors in Dynamic Positioning Operations: Implications for Training and Safety

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Abstract: Dynamic positioning operations are highly automated maritime activities, yet human performance still plays a crucial role. Compiling a dataset covering incidents happening between 2016 and 2025, this paper examines whether a previously proposed model predicting the likelihood of dynamic positioning incidents being caused by human factors is still valid for the new data. The model was originally developed for dynamic positioning incidents covering the period 2007 - 2015, with the percentage of thrusters online as the independent variable which helps predict the human-related cause for the incidents. Using the newer database, the research presents a temporal validation based on longitudinal incident data and discusses the implications for maritime education in general and dynamic positioning training in particular. The results present the relevance of human-related factors in recent DP incidents, having 35 out of 77 valid cases classified as having either a main or secondary human-related cause. However, the original relationship between thruster availability and human-related causation was not replicated in the updated data. These findings suggest that human-related dynamic positioning risk cannot be assumed from a single technical indicator.

Keywords: Dynamic Positioning; human error; temporal validation; maritime safety; simulator-based training

1. Introduction

Dynamic positioning (DP) is essential in offshore marine operations where vessels must maintain position and heading with a high degree of accuracy, often without the use of anchors or mooring lines. They are used in drilling, diving support, remotely operated vehicle operations, subsea construction, cable and pipe laying, shuttle tanker operations and other activities in which station keeping is critical. In these operations, even a limited loss of position may interrupt the task, damage offshore or subsea infrastructure, create collision threat, endanger personnel or lead to environmental consequences. For this reason, DP safety depends on the interaction of technical redundancy, operational planning, procedural discipline and continuous human supervision.

The technical complexity of DP operations has been widely documented in the literature. DP systems integrate propulsion, power generation, position reference systems, motion sensors, environmental sensors and control algorithms in order to counteract external forces and maintain vessel position. Sørensen (2011) describes DP as an integrated control problem in which vessel dynamics, sensors, actuators and control allocation must operate together. From a safety perspective, Chen et al.(2008) showed that DP operations on mobile offshore drilling units should be treated as system-level safety problems, rather than as purely technical control tasks. This is particularly relevant for drilling operations, where the consequences of position loss may be serious due to the proximity of the vessel to the well, riser system or other offshore assets.

Although DP systems are highly automated, safe operations do not depend only on automation. DP operators remain responsible for monitoring the system automations, interpret eventual alarms, communicating with other operational teams and responding to critical situations. In this sense, the human role is not substituted by technology, but rather changed by it. The operator is no longer in charge of controlling vessel movement directly, but is also supervising an automated system, interpreting multiple sources of information and deciding when an intervention is necessary. Øvergård et al. (2015) linked critical DP incidents to operators' situation awareness and decision-making, showing that human performance remains central in complex DP scenarios. Hogenboom et al. (2020) further demonstrated that the allocation of control functions in DP systems can

influence human reliability, reinforcing the idea that human performance must be analysed in relation to the design and operation of the technical system.

Therefore, human factors in DP operations should not be understood only as individual factor, but as part of a more complex system, which depends on ergonomy, workload, training, procedures, communication, organisational team culture and operational pressure. DP incidents involving human factors may involve inadequate monitoring, incorrect interpretation of alarms, procedural non-compliance or inappropriate decision-making under pressure. However, these actions usually emerge within a broader operational context. Dong, Vinnem and Utne (2017) showed that learning from DP incidents requires attention to the interaction between technical failures, operational circumstances and human response. Recent DP risk research has also continued to emphasise the contribution of human factors, particularly in relation to monitoring, decision-making, competence and operational control (Chervinskyi et al., 2026).

Previous studies have attempted to analyse DP incidents using statistical and data-driven approaches. Sánchez-Varela et al. (2021a) applied binary logistic regression to predict the loss of position during DP drilling operations. Furthermore, in a related study, Sánchez-Varela et al. (2021b) developed a model to estimate the likelihood that a DP drilling incident was caused by human factors. In that earlier model, the percentage of thrusters online was identified as a significant predictor of human-related causation. This provided an initial statistical basis for estimating the likelihood of human contribution in DP drilling incidents. More recent work by Sánchez-Varela et al. (2024) examined human-related incidents across DP operations and confirmed that the human element remains a relevant component of DP incident causation. Data-driven approaches can present relationships between incident factors which are not immediately evident when performing a descriptive analysis alone, as indicated by Sahin and Bolat (2024).

However, models which are developed from historical incident data cannot be assumed to remain valid indefinitely, since especially technology in the maritime industry, but also training and competence requirements, and reporting systems evolve over time. A predictor that was relevant in an earlier dataset may lose explanatory value in a later period if the operational context has changed. This issue is central to the validation of prediction models. Ramspek et al. (2021) explain that external validation is necessary to determine whether a model performs adequately outside the data from which it was originally developed. Binuya et al. (2022) further emphasise that models may require recalibration, revision or extension when applied to new populations, time periods or contexts. For the present study, this means that the earlier human-factor likelihood model should be tested using more recent DP incident data before its assumptions are applied to current operations.

This paper applies temporal validation using longitudinal incident data. The term “temporal validation” refers to testing whether a model developed from one time period remains applicable when applied to a later time period. The term “longitudinal incident data” refers to the fact that the data cover a sequence of reported DP incidents over several years. This distinction is important because the purpose of the study is not only to calculate whether the previous model still works, but also to examine whether the relationship between human-related causation and selected technical, operational and environmental variables remains stable over time.

The importance of this question is significant. Since isolated technical variables do not adequately explain human-related DP incidents, then DP training should not concentrate only on equipment configuration or system status. Simulator-based training is particularly important because it allows operators to experience abnormal situations, degraded redundancy, alarm sequences, environmental changes and time pressure in a controlled learning environment. Although simulator training can support the development of human-factor competence in offshore operations (Håvold et al., 2015), Mallam et al. (2019) argued that maritime education and training must adapt to the digital era by integrating more realistic, technology-supported learning environments. Katakura et al. (2025) focused directly on simulator-based training offering emergency response for DP operators, supporting the need to use simulation to increase the preparedness for critical DP situations.

The objective of this paper is to evaluate the temporal validity of a previously developed human-error likelihood model for DP drilling incidents using updated IMCA-reported DP incident data, and to discuss the implications for DP training, simulator-based competence assessment and maritime education. The specific objectives are: to examine the presence of human-related factors in the updated dataset, assess whether the earlier model remains applicable, determine whether selected technical, operational and environmental

variables exhibit explanatory value, and consider how the findings can inform human-centred training for digitally intensive DP operations.

2. Methodology

This study applies a retrospective observational design to analyse reported DP incidents. In this sense, the study performs temporal validation using longitudinal incident data, following the general principle that prediction models should be tested beyond the data from which they were originally developed before being applied to new contexts (Ramspek et al., 2021).

The dataset was compiled from DP incident and event reports published by the International Marine Contractors Association (IMCA). IMCA DP station keeping reports provide industry safety information on DP incidents, undesired events and observations, and are intended to support learning within the offshore and DP community (International Marine Contractors Association (IMCA), 2026). The updated dataset covers the period from 2016 to 2025 and was selected because it represents a later operational period than the one used to develop the original human-error likelihood model.

Initially, 86 cases were identified for the updated period. Cases with missing technical, operational or environmental variables required for the analysis were excluded, leaving 77 valid cases for statistical examination.

The dependent variable was the presence of a human-related cause in the DP incident, either as the main or secondary cause. This variable was coded as binary, taking the value 0 if there was no human-related cause, and the value 1 if there was evidenced a human-related cause.

The independent variables were selected from the technical, operational and environmental information available in the IMCA reports. They included variables related to DP system configuration, position reference systems, environmental conditions and operational context. These variables were selected because they are relevant to DP system performance and station keeping safety, and because comparable variables were used in previous DP incident modelling studies (Sanchez-Varela et al., 2021a).

Next, the model developed from the earlier database (2007-2015) was applied to the updated dataset. The original model identified the percentage of thrusters online as a significant predictor of whether a DP incident had a human-related cause (Sanchez-Varela et al., 2024). The model is given by the following expression:

$$Z = 1.489 - 0.031 \cdot percentage\ of\ thrusters\ online \quad (1)$$

In the present study, this relationship was tested in the updated dataset to determine whether the original predictor retained explanatory value.

Finally, the result of the validation was interpreted considering its relation to DP training and competence development, simulator scenario development and competence assessment.

3. Results and discussion

After excluding cases with missing technical, operational or environmental information required for the analysis, the database comprises 77 valid cases. Out of these, 35 cases (45.5%) of the valid sample, were classified as having either a main or secondary human-related cause.

This result is important because it confirms that human cause remains sufficiently present in recent DP incident data, although DP systems are increasingly automated and technically sophisticated. This supports the main statement of the paper: DP safety cannot be understood only through technical availability, redundancy or environmental conditions. It must also be examined through the way operators monitor, interpret and manage the DP system during operations.

In Figure 1, the DP operations stratified by whether caused by a human factor or not, are shown.

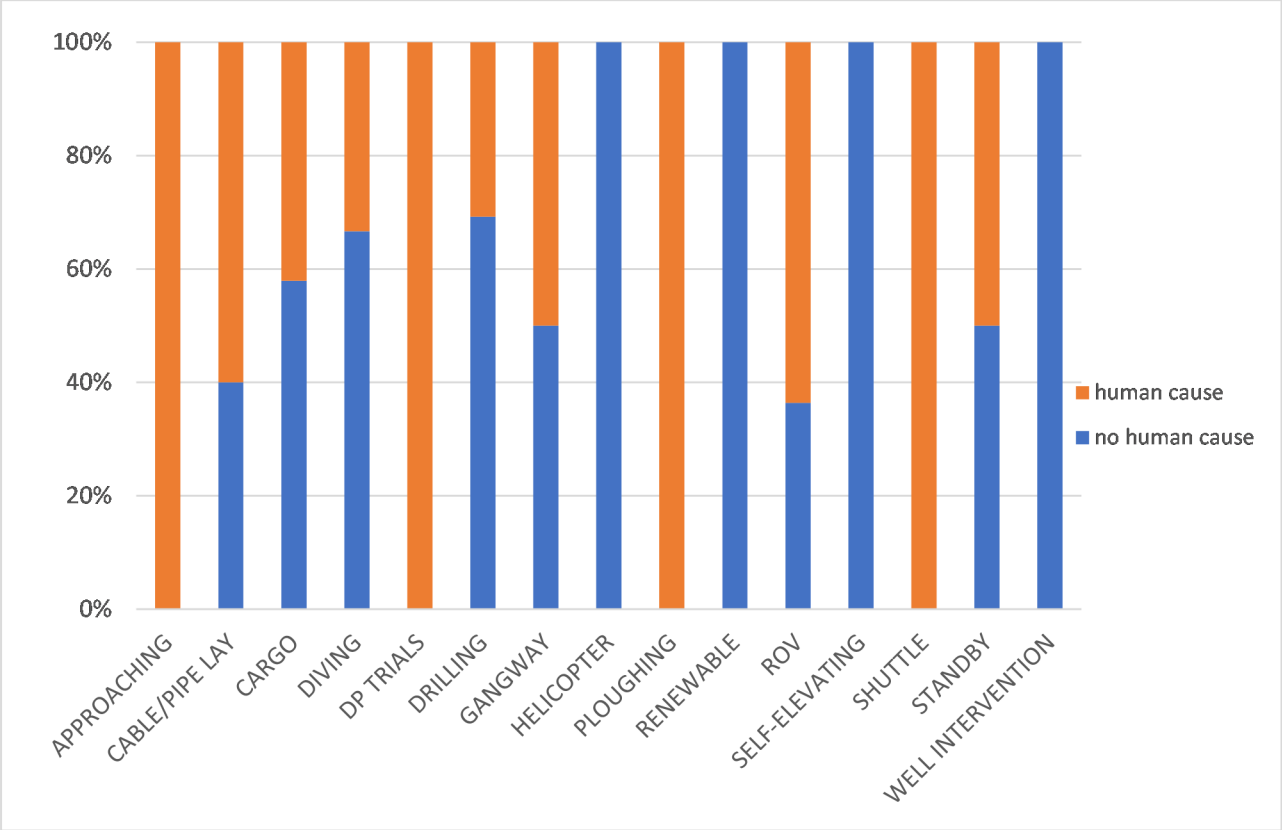


Figure 1. The percentage of incidents having a human cause for each operation in progress.

From an educational perspective, the continued presence of human-related factors supports the need to maintain strong human-factor content in DP training. From a methodological perspective, it justifies testing whether the previous model predicting human-related likelihood still explains this causality for the more recent reporting period.

The variables included in the study and their main statistics are shown in Table 1.

Table 1.Descriptive statistics for the independent variables considered in the research (n = 77).

Variables	Mean	Standard Error	Median	Standard deviation	Minimum	Maximum
Water depth (m)	561,83	103,60	100,00	909,11	13,00	4800,00
Percentage of thrusters online	96,53	0,88	100,00	7,69	71,43	100,00
Percentage of generators online	70,52	2,32	66,67	20,39	33,33	100,00
No. of DGNSS	2,43	0,09	2,00	0,82	1,00	5,00
No. of HPR	0,71	0,09	1,00	0,76	0,00	2,00
No. of Tautwire	0,36	0,08	0,00	0,69	0,00	2,00
No. of Laser	0,32	0,05	0,00	0,47	0,00	1,00
No. of Microwave Radar	0,17	0,05	0,00	0,41	0,00	2,00
No. of Artemis	0,01	0,01	0,00	0,11	0,00	1,00
No. of Gyros	2,92	0,04	3,00	0,31	1,00	3,00
No. of MRU	2,55	0,06	3,00	0,55	1,00	3,00
No. of Wind sensors	2,56	0,07	3,00	0,64	1,00	4,00

Variables	Mean	Standard Error	Median	Standard deviation	Minimum	Maximum
Wind force (knots)	13,22	1,04	11,00	9,10	1,00	50,00
Current (knots)	1,33	0,15	1,00	1,31	0,00	9,50
WaveHeight (m)	1400,00	0.161	1000,00	1413,00	0,10	10000,00
Visibility	2,83	0,05	3,00	0,41	1,00	3,00

The previous human-error likelihood model identified the percentage of thrusters online as a significant predictor of whether an incident had a human-related cause. When applying this newer database,

The validation result did not support the direct transferability of the original relationship. In the updated drilling subset, the median percentage of thrusters online was 100% for both human-related and non-human-related cases. In addition, all human-related drilling cases occurred with 100% of thrusters online, whereas reduced thruster availability occurred only in non-human-related cases.

This finding should not be interpreted as a failure of the earlier model. The original model was valid for the data and operational context from which it was developed. However, the updated evidence indicates that the same predictor does not behave similarly in the later dataset. This is precisely why temporal validation is necessary: a model based on historical incident data may lose explanatory value when reporting practices, operational conditions, training approaches or technical systems evolve.

The most important interpretation is that technical availability alone does not appear sufficient to explain human-related causation in the updated sample. In the earlier model, reduced thruster availability was associated with a higher likelihood of human-error-related causation, especially in drilling operations. In the updated data, however, human-related drilling incidents occurred even when all thrusters were online. This suggests that human-related risk may emerge not only from degraded technical configuration, but also from how operators interpret and manage a situation when the technical system appears available.

For DP training, this is a significant point. Training scenarios should not only focus on obvious technical degradation, such as loss of thrusters or reduced redundancy. They should also include situations in which the system appears technically available, but the operator must still detect weak signals, interpret alarms, monitor system behaviour, communicate effectively and decide whether intervention is required. This interpretation also shows that human-related DP incidents should not be addressed solely by technical or configuration-based predictors. The updated dataset confirms the presence of human-related causes, but it does not explain the underlying cognitive or organisational mechanisms through which these causes develop. Factors such as workload, fatigue, communication quality, team coordination, alarm interpretation, decision-making under pressure, safety culture, and organisational constraints may all influence operator performance in DP operations. However, these factors are not systematically captured in the IMCA reports and therefore cannot be directly analysed in the present study. For this reason, the findings should be interpreted as a quantitative indication of the continuing relevance of human-related factors, rather than as a complete explanation of their origin.

3.1 Limitations

Several limitations must be considered when interpreting the results. The primary limitation is that the dataset is based on IMCA-reported DP cases and should not be assumed to represent a complete global list of DP incidents. Since reporting is voluntary and published cases are selected for industry-learning purposes, it is not possible to determine whether the dataset is fully representative of all DP incidents. Therefore, the results describe patterns within reported cases rather than the absolute frequency of human-related DP incidents worldwide.

Furthermore, the comparison between the earlier and updated periods may be affected by changes in reporting practices. IMCA DP station-keeping reporting evolved over time, especially from 2016 onward (International Marine Contractors Association (IMCA), 2016), and this may influence the level of detail, classification and comparability of available cases. As a result, differences between periods may reflect not only changes in DP operations or human performance, but also changes in reporting structure.

Moreover, the updated drilling subset is small, thus limiting the statistical power of the validation. The result does not prove that thrusters online are not relevant to human-related causation; rather, it shows that the previously identified relationship was not reproduced in the available updated drilling cases. What is more, the available variables mainly describe technical, environmental and operational conditions. They do not directly measure cognitive, organisational or procedural factors such as situation awareness, workload, fatigue, alarm interpretation, team communication, training quality or safety culture. These factors are central to understanding human-related causation, but they are not consistently available in the incident reports.

4. Conclusions

The main objective of this paper is to determine whether a previously developed model showing the likelihood of DP incidents being caused by human factors remains valid when applied to a more recent dataset, based on IMCA-reported events. The results confirm that human-related factors remain important in recent DP incidents, with 35 out of 77 valid cases classified as having either a main or secondary human-related cause. However, the original relationship between thruster availability and human-related causation was not replicated in the updated data. This indicates that the percentage of thrusters online should not be applied uncritically as a predictor of human-related causation in newer DP incident data.

The findings do not refute the earlier model, but they show that incident-based models require temporal validation before being transferred to new operational periods. Changes in reporting practices, operational context, DP technology, training approaches and competence requirements may affect the stability of previously identified relationships. In this case, the reporting principle was identified as a possible cause for this digression from the previous model.

Future research should therefore complement quantitative incident analysis with qualitative human-factors approaches, including interviews with DP operators, instructors, investigators and safety managers, as well as simulator-based observation studies. Such approaches would make it possible to examine cognitive and organisational dimensions that are not systematically captured in the IMCA reports, including workload, fatigue, communication, team coordination, decision-making, safety culture and organisational pressure. This would provide a stronger basis for developing simulator-based training scenarios and competence-development strategies aimed at reducing human-related DP incidents.

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Smart Ports in the Digital Era: The Role of Information Technologies in Enhancing Efficiency and Competitiveness

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Abstract: The increasing complexity of logistics chains and the growth of global trade highlight the need for smart ports as a key mechanism for achieving economic sustainability, competitiveness, and operational efficiency in the maritime sector. Smart ports are based on advanced digital technologies and integrated business information systems that enhance security, transparency, efficiency, and environmental performance. This paper examines the role of business information systems in the digital transformation of ports, focusing on the integration of ERP, TOS, and PCS systems into terminal operations. The analysis explores their impact on resource optimisation, cost reduction, productivity, and service quality, as well as challenges of their implementation. Findings show that Rotterdam, Singapore, and Hamburg differ in digital maturity, priorities, and strategies. Rotterdam and Singapore demonstrate higher levels of digital integration and automation, with Rotterdam leading in advanced technologies such as digital twins and artificial intelligence, while Singapore applies a centralised approach. Hamburg remains at an earlier stage, focusing on sustainability and energy efficiency. Despite these differences, real-time data integration, interoperability, and process automation significantly improve operational efficiency and competitiveness, while supporting sustainability goals. The paper provides recommendations for adaptable digital solutions and emphasises the importance of strategic digitalisation for long-term port competitiveness.

Keywords: smart ports; digital transformation; economic sustainability; business information systems; port terminals

1. Introduction

Maritime transport underpins global trade, accounting for over 80% of world merchandise by volume (UNCTAD, 2025), with ports serving as critical nodes integrating maritime, land, and information flows. Increasing supply chain complexity and growing demands for efficiency, resilience, and sustainability have exposed the limitations of traditional, fragmented port management models, accelerating the emergence of smart ports as a dominant paradigm in maritime logistics. Smart ports are characterised by the integration of advanced digital technologies – such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and digital twins – with organisational processes and information systems. In this context, business information systems (BIS), including Enterprise Resource Planning (ERP), Terminal Operating Systems (TOS), and Port Community Systems (PCS), play a central role in enabling real-time data exchange, process automation, and data-driven decision-making. Despite growing scholarly attention (Heilig et al., 2017; Tijan et al., 2021), existing research predominantly examines individual technologies or single-port cases, while overlooking the systemic role of integrated business information systems. Moreover, comparative analyses across ports with differing levels of digital maturity and institutional contexts remain limited, particularly regarding the relationship between system integration, performance outcomes, and sustainability.

This research addresses these gaps by conceptualising port digital transformation as a system-level integration of business information systems and by conducting a comparative analysis of Rotterdam, Singapore, and Hamburg. It examines how differences in digital maturity, implementation strategies, and governance contexts influence operational efficiency, competitiveness, and sustainability outcomes. The research contributes by positioning BIS as the core infrastructural layer of smart ports and by developing a structured analytical framework applicable across different stages of digital transformation. The research is guided by the following research questions: (1) how BIS are integrated into port operations; (2) how digital technologies

interact with core systems; (3) how digital integration influences efficiency, service quality, and sustainability; (4) how digital maturity and strategic orientation differ across ports; and (5) what insights can inform digital transformation strategies. Accordingly, the following hypotheses are proposed: H1: BIS integration positively influences operational efficiency; H2: higher digital maturity enhances competitiveness and performance; H3: advanced digital technologies contribute to sustainability; and H4: institutional and governance differences shape digital transformation outcomes. The remainder of the paper is structured as follows. Section 2 reviews the literature, Section 3 presents the methodology, Section 4 reports the results, Section 5 discusses the findings, and Section 6 concludes the paper.

2. Literature Review – Summary of Previous Studies on Smart Ports

The concept of smart ports has emerged in response to increasing supply chain complexity and the need for efficient, resilient, and sustainable port operations. Ports are evolving into integrated logistics platforms supported by digital technologies and intermodal connectivity (Rodrigue, 2020). Smart ports are defined as systems that leverage advanced technologies and integrated information systems to optimise processes, improve decision-making, and enhance overall performance (Heilig et al., 2017; Tijan et al., 2021). Accordingly, digital transformation in ports represents not only technological adoption but also a broader organisational shift involving the integration of processes, stakeholders, and data flows into a unified digital ecosystem (Fruth and Teuteberg, 2017). This transformation is commonly conceptualised through digital maturity models progressing from isolated systems to fully integrated, data-driven environments, with the three-stage model proposed by Heilig et al. (2017) providing a key theoretical foundation. A substantial body of literature highlights the role of advanced digital technologies in enabling smart port development. Key technologies include the Internet of Things (IoT), artificial intelligence (AI), big data analytics, digital twins, and blockchain (Bouhlal et al., 2022; Fruth and Teuteberg, 2017). These technologies support real-time monitoring, predictive analytics, and process optimisation, contributing to improved operational efficiency. For example, IoT and AI applications enable predictive planning and congestion reduction in leading ports such as Rotterdam and Singapore (Heilig et al., 2017), while IoT-based systems enhance cargo tracking and logistics coordination (Bouhlal et al., 2022). However, the literature emphasises that technological adoption alone is insufficient; its effectiveness depends on integration within broader information systems, as fragmented implementation may limit systemic improvements (Fruth and Teuteberg, 2017). While digital technologies often receive primary attention, business information systems (BIS) are identified as the core infrastructure of smart ports (Lam and Bai, 2016; Tijan et al., 2021). Systems such as Enterprise Resource Planning (ERP), Terminal Operating Systems (TOS), and Port Community Systems (PCS) enable process integration, stakeholder coordination, and real-time data exchange across the port ecosystem. The integration of IoT technologies with BIS further enhances transparency and operational efficiency (Aylak, 2022), while interoperability is recognised as a key success factor facilitating communication among stakeholders (Lam and Bai, 2016). Despite their importance, existing research rarely examines these systems as an integrated whole, instead focusing on individual technological components.

Sustainability represents a central dimension of smart port development, driven by regulatory pressures and global environmental challenges. Digitalisation enables energy optimisation, emission reduction, and the implementation of green technologies, while supporting real-time environmental monitoring and more efficient logistics planning (Acciaro et al., 2014; Lam and Notteboom, 2014). In addition to environmental benefits, digital transformation contributes to economic efficiency and socially responsible operations, aligning with broader sustainable development goals (Acciaro et al., 2014). However, the effectiveness of these measures depends on their integration within broader digital transformation strategies. Comparative studies of leading ports provide insights into different digital transformation pathways. Ports such as Rotterdam, Singapore, and Hamburg are frequently identified as benchmark cases (Heilig et al., 2017). Rotterdam represents a technology-driven model characterised by advanced digital platforms, Singapore reflects a centralised and state-supported approach with strong automation and system integration, while Hamburg demonstrates a sustainability-oriented pathway focused on environmental innovation. These cases indicate that digital transformation varies depending on governance models, strategic priorities, and institutional contexts. Importantly, digital maturity is not determined solely by technological adoption but also by organisational capacity and stakeholder coordination (Tijan et al., 2021). Taken together, the literature indicates that smart port development is a multidimensional process involving the interaction of digital technologies, information systems, and sustainability objectives.

Recent research further emphasises the importance of integrated business information systems in improving efficiency, competitiveness, and sustainability in port operations (Pavlinović et al., 2023). However, several gaps remain evident, including the limited focus on the integrated role of BIS, the lack of holistic approaches combining technological, operational, and sustainability dimensions, and insufficient comparative analyses across different institutional contexts. Accordingly, there is a need for research that adopts a comprehensive and system-oriented perspective, examining how the integration of business information systems and digital technologies jointly influences port performance and sustainability. This research addresses these gaps through a structured comparative analysis of leading ports.

Table 1. Summary of Previous Studies on Smart Ports

Author(s)	Focus Area	Key Concepts / Technologies	Methodology	Key Findings
Heilig, Lalla-Ruiz and Voß (2017)	Digital maturity of ports	Digitalisation stages, smart ports, automation	Conceptual framework	Three-stage port digital transformation model
Acciaro et al. (2014)	Sustainability in ports	Energy management, green ports	Case study / analytical	Digital systems support energy efficiency and emission reduction
Fruth and Teuteberg (2017)	Digitalisation in maritime logistics	IoT, digital platforms, logistics integration	Literature review	Technologies improve coordination and transparency
Lam and Bai (2016)	Port competitiveness and resilience	Supply chain integration, quality function deployment	Analytical model	System integration enhances resilience and service quality
Tijan et al. (2021)	Digital transformation in maritime transport	ICT, digitalisation, smart logistics	Review / conceptual	Digitalisation drives efficiency and innovation
Rodrigue (2020)	Port development and logistics	Port evolution, intermodal systems	Theoretical / analytical	Ports evolve into integrated digital logistics platforms
Aylak (2022)	Data integration in ports	IoT + information systems	Empirical / analytical	IoT integration improves transparency and efficiency
Bouhlal et al. (2022)	IoT-based smart port systems	IoT architecture, smart infrastructure	Applied research	IoT enhances monitoring and automation
Lam and Notteboom (2014)	Sustainable port development	Green logistics, environmental management	Review	Sustainability integrated into port strategies
Pavlinović et al. (2023)	Smart ports and BIS integration	ERP, TOS, PCS, digital transformation	Comparative analysis	Integrated systems improve efficiency, competitiveness, and sustainability

Table 1 summarises key contributions from previous studies on smart ports, highlighting the dominant focus on digital technologies and sustainability, while indicating a limited number of studies adopting a holistic, system-oriented perspective on the role of business information systems.

3. Methodology

This research adopts a qualitative comparative case study design to examine the role of business information systems in port digital transformation. The approach is suitable for analysing complex socio-technical systems and real-world phenomena (Yin, 2018) and is grounded in an interpretative paradigm aimed at understanding how digital technologies and information systems are implemented and integrated within port environments (Saunders et al., 2019). A multiple-case design is applied to enable cross-case comparison and the identification of patterns across different levels of digital maturity (Heilig et al., 2017). The analysis focuses on three globally significant ports: Rotterdam, Singapore, and Hamburg. The cases were selected through purposive sampling based on their strategic relevance, level of digital development, and data availability (Yin, 2018). Rotterdam represents a technology-driven model, Singapore a centralised and state-supported model, and Hamburg a sustainability-oriented model, enabling comparison of different digital transformation pathways. The selection of Rotterdam, Singapore, and Hamburg was based on analytical rather than geographical considerations. These ports represent internationally recognised benchmark cases that illustrate three distinct pathways of smart port development. Rotterdam was selected because it represents a technology-driven model characterised by advanced digital twins, AI applications, and integrated digital platforms. Singapore represents a centralised and government-supported model distinguished by high levels of automation and national digital integration. Hamburg was selected because it illustrates a sustainability-oriented approach, combining digital technologies with environmental management and smart urban logistics. Together, these cases provide sufficient variation in governance models, strategic priorities, and digital maturity, enabling meaningful cross-case comparison and analytical replication. The research relies exclusively on secondary data, including official port reports, scientific literature, and industry publications. Secondary sources were selected based on four criteria: credibility, relevance, recency, and comparability. The analysis prioritised peer-reviewed literature, official reports, and strategic documents directly addressing digital transformation in ports. Seminal studies were retained to provide the theoretical background, while only sources enabling consistent comparison across Rotterdam, Hamburg, and Singapore were included in the final analysis. These sources provide insights into port strategies, technological implementation, and operational practices, while their combination enables data triangulation and enhances the reliability of the findings (Saunders et al., 2019). The analysis integrates several qualitative methods within a structured framework. Thematic analysis is used to identify key dimensions of digital transformation, including digital technologies, business information systems, operational efficiency, sustainability, and institutional factors (Heilig et al., 2017). For the purposes of this study, operational efficiency is defined as the extent to which digital technologies and business information systems improve the speed, coordination, reliability, and resource utilisation of port operations. Because the study is based on qualitative secondary evidence rather than a single standardised metric, operational efficiency was assessed through recurrent indicators reported in the literature and in official port documentation, including vessel turnaround time, berth and terminal coordination, cargo-handling and yard-process optimisation, reduction of congestion and operational delays, real-time information exchange, interoperability among ERP, TOS, and PCS systems, automation of operational tasks, predictive planning, and the synchronisation of logistics flows. Performance outcomes were assessed more broadly as documented organisational and system-level effects of digital transformation, including improvements in service quality, stakeholder coordination, decision-making capability, competitiveness, resilience, and sustainability, especially energy efficiency and emissions-related initiatives. This distinction allows the analysis to differentiate between immediate operational improvements and wider strategic outcomes of digital transformation (Acciaro et al., 2014; Fruth and Teuteberg, 2017; Lam & Bai, 2016; Tijan et al., 2021). Comparative analysis is conducted using a structured matrix to assess differences in digital maturity, technology adoption, and strategic orientation across ports. SWOT and PESTLE analyses are applied to examine internal and external factors influencing digital transformation. The conceptual model links digital technologies and business information systems to the level of integration (digital maturity), which influences operational efficiency, competitiveness, and sustainability outcomes, if higher levels of integration lead to improved performance. The selected methodology is appropriate for analysing port digital transformation as a complex socio-technical phenomenon (Heilig et al., 2017). The case study approach enables context-sensitive analysis (Yin, 2018), while the comparative design supports the identification of patterns across different institutional settings. The use of multiple methods ensures methodological triangulation and strengthens the robustness of the findings (Saunders et al., 2019). The reliance on secondary data is justified by the availability of comprehensive information on globally leading ports.

4. Results

4.1. Port of Rotterdam

The Port of Rotterdam represents one of the most advanced examples of digital transformation in the maritime sector and can be characterised as a technology-driven smart port model. A key element of Rotterdam's digital strategy is the development of a digital twin of the port infrastructure, integrating real-time data from IoT sensors, weather systems, and vessel traffic management platforms (Port of Rotterdam Authority, 2023). This digital environment enables the simulation of operational scenarios, prediction of congestion, and optimisation of vessel scheduling, resulting in high operational efficiency and reduced turnaround times. In addition, Rotterdam has implemented advanced digital platforms such as PortXchange, which facilitate real-time data exchange among stakeholders, including shipping companies, terminal operators, and logistics providers (Port of Rotterdam Authority, 2023). This enhances coordination, reduces delays, and improves transparency across the port ecosystem. The extensive use of IoT technologies, combined with AI-based analytics, supports continuous monitoring of cargo flows and infrastructure, enabling predictive planning and data-driven decision-making. From a sustainability perspective, digital technologies are closely integrated with environmental initiatives, including energy optimisation and emission reduction strategies, positioning Rotterdam as a leading example of green port development (Port of Rotterdam Authority, 2023). Rotterdam's digital transformation is thus characterised by a very high level of maturity, supported by strong system integration, advanced technological capabilities, and a clear strategic orientation towards innovation and sustainability.

4.2. Port of Singapore

The Port of Singapore represents a centralised and highly integrated model of digital transformation, supported by strong institutional governance and long-term strategic planning. A key development is the implementation of the Tuas Mega Port, one of the most advanced automated port systems globally, incorporating autonomous guided vehicles (AGVs), AI-driven logistics systems, and digital twin technologies (Maritime and Port Authority of Singapore, 2023). Singapore's digital transformation is further supported by national-level platforms such as digitalPORT@SG, which enable seamless coordination among maritime stakeholders through real-time data exchange and integrated information systems (Maritime and Port Authority of Singapore, 2023). This integrated digital environment ensures high levels of interoperability and operational efficiency across the port ecosystem. A key strength of Singapore's approach lies in its centralised governance model, in which state institutions play a leading role in driving digital innovation and infrastructure development. This institutional framework enables rapid technology adoption and a high degree of system interoperability. From a sustainability perspective, digital solutions are closely aligned with environmental strategies, including energy-efficient operations and emission reduction initiatives (Maritime and Port Authority of Singapore, 2023). Singapore's digital transformation is thus characterised by a very high level of integration and automation, supported by a strong emphasis on efficiency, scalability, and coordinated strategic development.

4.3. Port of Hamburg

The Port of Hamburg represents a sustainability-oriented model of digital transformation, with a strong focus on smart logistics and environmental innovation. The SmartPORT initiative integrates digital technologies to optimise traffic flows, logistics processes, and infrastructure management, including the use of sensor networks, intelligent transport systems, and real-time data platforms (Hamburg Port Authority, n.d.). Digital solutions are applied to both maritime and hinterland transport, improving coordination between port operations and urban mobility systems. These technologies contribute to reduced congestion and enhanced operational efficiency. Compared to Rotterdam and Singapore, Hamburg exhibits a high but comparatively lower level of digital maturity, with ongoing development of advanced technologies such as digital twins. Nevertheless, its strategic emphasis on sustainability distinguishes it from other ports. Hamburg has implemented a range of green initiatives, including onshore power supply systems, renewable energy integration, and energy-efficient logistics solutions, reflecting a strong commitment to environmental sustainability (Hamburg Port Authority, n.d.). At the same time, the port faces structural constraints related to

physical limitations, such as restricted water depth and capacity, as well as a comparatively slower pace of technological adoption. Hamburg's digital transformation is therefore characterised by a strategic alignment between technological development and sustainability objectives, with a particular emphasis on integration with the urban environment.

4.4. Comparative Analysis of Digital Maturity

Building on the individual case analyses, Table 2 presents a comparative assessment of digital maturity across the selected ports using a 1–5 scale. The comparison highlights differences in technological implementation, system integration, and strategic orientation, providing a structured basis for evaluating transformation impacts and performance outcomes.

Table 2. Digital Maturity Comparison of Selected Ports (1–5 Scale)

Dimension	Rotterdam	Singapore	Hamburg
Digital Twin Implementation	5 – Fully operational digital twin	4 – Advanced, expanding	3 – Partial implementation
IoT Infrastructure	5 – Extensive real-time monitoring	5 – Highly developed, integrated	4 – Strong, less integrated
AI and Data Analytics	5 – Predictive planning and optimisation	5 – AI-driven automation	4 – Applied, less advanced
BIS Integration (ERP, TOS, PCS)	5 – Fully integrated platforms	5 – National-level systems	4 – Integrated, less comprehensive
Interoperability & Data Sharing	5 – Seamless real-time exchange	5 – Highly interoperable	4 – Developing interoperability
Automation Level	5 – Advanced automation	5 – Fully automated terminals	3 – Moderate automation
Sustainability Integration	5 – Digital + environmental strategies	5 – Strong integration	5 – Core strategic focus
Institutional Support	5 – Strong strategic support	5 – Centralised governance	4 – Less centralised
Performance Outcomes	Very high	Very high	High

The digital maturity scale (1–5) was developed as a qualitative framework to assess the level of digital transformation across selected ports, based on established concepts in the literature (e.g. Heilig et al., 2017). It captures three key dimensions: (1) implementation of digital technologies (IoT, AI, digital twins), (2) integration of business information systems (ERP, TOS, PCS), and (3) their operational and strategic impact. Each dimension was evaluated using five predefined criteria: level of implementation, degree of system integration, technological sophistication, operational impact, and strategic importance within the port development model. Scores were assigned based on evidence obtained from peer-reviewed literature, official port reports, and strategic documents. This approach provides a transparent and consistent basis for comparing the digital maturity of the selected ports. The scale ranges from Level 1 (very low maturity) to Level 5 (very high maturity), with each level representing a distinct stage of development. Level 1 reflects minimal digitalisation and predominantly manual processes. Level 2 indicates initial adoption of isolated solutions with limited impact. Level 3 involves partial implementation within specific functions, with moderate optimisation. Level 4 represents advanced technologies, strong system integration, and improved efficiency and decision-making. Level 5 corresponds to a fully integrated smart port ecosystem, characterised by real-time data exchange, automation, predictive analytics, and high performance across operational and sustainability dimensions. The assessment is based on qualitative analysis of secondary data (port reports, strategic documents, and scientific literature), using a comparative approach to ensure consistency and analytical transparency across cases.

To further illustrate the impact of digital transformation, Table 3 provides a structured summary of key findings across the selected ports, focusing on technological adoption, system integration, and performance outcomes.

Table 3. Summary of Results for Selected Smart Ports

Dimension	Rotterdam	Singapore	Hamburg
Digital Transformation Model	Technology-driven smart port	Centralised and state-supported model	Sustainability-oriented smart port
Key Technologies	Digital twin, IoT, AI, PortXchange	AI, digital twin, AGVs, digitalPORT@SG	IoT sensors, SmartPORT, intelligent traffic systems
Business Information Systems	Highly integrated ERP, TOS, PCS	Fully integrated national-level systems	Integrated systems, but less advanced

Data Integration & Interoperability	Real-time data exchange across stakeholders	High level of integration via central platforms	Moderate, still developing
Operational Efficiency	Very high (optimised scheduling, reduced delays)	Very high (automation and AI optimisation)	High (improved logistics and coordination)
Automation Level	Advanced automation and predictive systems	Very high (autonomous and automated terminals)	Moderate (focus on coordination)
Sustainability Integration	Strong integration of digital and environmental strategies	Strong integration with energy-efficient operations	Core focus on sustainability and green technologies
Key Strengths	Advanced technology and system integration	Centralised governance and high automation	Sustainability focus and urban integration
Key Challenges	System complexity and cybersecurity risks	Capacity constraints and trade dependency	Physical constraints and slower digital adoption
Performance Outcome	Very high	Very high	High

Table 3 highlights that higher levels of digital maturity are directly associated with improved performance outcomes, particularly in terms of operational efficiency, automation, and system integration. While Rotterdam and Singapore demonstrate highly advanced, technology-driven models, Hamburg follows a sustainability-oriented pathway, achieving strong environmental performance despite a comparatively lower level of technological integration.

5. Discussion

The findings confirm that the integration of business information systems (ERP, TOS, PCS) significantly enhances operational efficiency in port systems (H1). Ports with higher levels of system integration, such as Rotterdam and Singapore, demonstrate superior performance through real-time coordination, optimised scheduling, and automated decision-making, whereas Hamburg, despite a high level of integration, places greater emphasis on coordination rather than full automation. These results indicate that BIS integration functions as a key enabler of efficiency by supporting real-time data exchange and process synchronisation, consistent with previous research (Lam & Bai, 2016; Fruth & Teuteberg, 2017). Furthermore, the results indicate that higher levels of digital maturity are associated with improved competitiveness and service performance (H2). Rotterdam and Singapore, characterised by very high digital maturity, exhibit advanced capabilities in predictive decision-making, automation, and optimisation of logistics flows, resulting in enhanced service quality and operational efficiency. Although Hamburg demonstrates a slightly lower level of technological advancement, it maintains competitiveness through its sustainability-oriented strategy. These findings indicate that digital maturity is not only a technological indicator but also a determinant of strategic positioning, consistent with prior studies (Heilig et al., 2017; Tijan et al., 2021).

The analysis further confirms that the adoption of advanced digital technologies contributes to improved environmental sustainability in port operations (H3). All three ports achieve high levels of sustainability integration through different approaches: Rotterdam focuses on energy optimisation and emission reduction, Singapore combines automation with energy-efficient systems, and Hamburg emphasises renewable energy integration and green infrastructure. Technologies such as IoT and AI enable real-time monitoring and optimisation of environmental performance, demonstrating that digitalisation and sustainability constitute mutually reinforcing processes (Acciaro et al., 2014; Lam and Notteboom, 2014). In addition, the findings indicate the significant influence of institutional frameworks and governance models on digital transformation outcomes (H4). Singapore's centralised and state-driven model enables rapid implementation and high levels of integration, Rotterdam benefits from a market-driven approach supported by strong stakeholder collaboration, whereas Hamburg follows a sustainability-oriented hybrid model. These differences indicate that digital transformation is not solely technology-driven but is substantially shaped by governance structures and strategic priorities (Heilig et al., 2017; Tijan et al., 2021).

Taken together, the comparative analysis reveals distinct digital transformation pathways among the observed ports. Rotterdam and Singapore represent highly advanced, technology-driven and integrated models, whereas Hamburg demonstrates a sustainability-oriented pathway with a slightly lower level of digital maturity. These findings indicate that digital transformation in ports is context-dependent and shaped by governance structures, strategic priorities, and resource availability. The results further indicate that system integration represents the key mechanism linking digital technologies with performance outcomes, reinforcing the central

role of business information systems in enhancing efficiency, competitiveness, and sustainability. These findings confirm all proposed hypotheses (H1–H4) and emphasise that successful port digital transformation requires not only technological adoption but also a strategically coordinated and system-oriented approach.

6. Conclusion

This research provides a system-oriented perspective on smart port development by highlighting the central role of business information systems in enabling digital transformation. The findings demonstrate that the effectiveness of digitalisation in ports depends not only on the adoption of advanced technologies but on their integration within coherent organisational and institutional frameworks. In this context, business information systems (ERP, TOS, PCS) function as the core infrastructural layer that supports data integration, coordination, and decision-making, while advanced technologies amplify their operational and strategic impact. The research contributes to the literature by advancing the concept of digital maturity as a multidimensional construct linked to performance and sustainability outcomes, and by emphasising the importance of system integration as a key transformation mechanism. From a practical perspective, the findings suggest that digital transformation strategies should prioritise system integration, align technological investments with existing infrastructures, and be adapted to specific institutional contexts. Furthermore, sustainability objectives should be embedded within digital strategies to ensure long-term value creation. Despite these contributions, the research is subject to several limitations, including reliance on secondary data, a limited number of case studies, and a qualitative assessment approach. Future research should focus on quantitative validation, broader comparative samples, and the use of primary data to deepen understanding of implementation processes. In addition, further studies could examine the role of emerging technologies and cybersecurity challenges, as well as the longitudinal evolution of digital transformation in port systems. Overall, the development of smart ports depends on the strategic integration of technologies, information systems, and governance structures, positioning digital transformation as a key determinant of future competitiveness and sustainability in the maritime sector.

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Bridging the Safety Gap: A Systematic Review of Maritime Education and Training Readiness for the Green Hydrogen and Ammonia

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Abstract: The maritime sector is rapidly transitioning towards zero-emission fuels following the International Maritime Organization (IMO)'s 2023 GHG Strategy, with green hydrogen and ammonia emerging as key alternatives. While research has focused on technological development, limited attention has been given to the readiness of Maritime Education and Training (MET). This study examines the alignment between emerging fuel systems and existing training frameworks using a systematic literature review guided by Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA). The findings identify a clear mismatch between the complexity of hydrogen and ammonia systems and current MET capabilities. To address this, a "Future-Ready" competency matrix is proposed, linking human-related operational risks to knowledge, practical skills, and simulator-based training. The framework supports improved workforce preparedness and safer implementation of alternative fuels.

Keywords: Green Hydrogen; Ammonia Safety; Competency Gap Analysis; Maritime Education and Training (MET); Decarbonisation

1. Introduction

The maritime sector is undergoing a rapid transition towards zero-emission fuels following the International Maritime Organization (IMO)'s 2023 GHG Strategy, with green hydrogen and ammonia emerging as key alternatives (DNV, 2023). While significant progress has been made in the technological development of these fuels, their adoption introduces new and complex safety challenges, including high flammability, toxicity, and system complexity (Kojima, 2024; Fetimi et al., 2025).

Existing research has largely focused on engineering solutions, fuel system design, and alternative fuel technologies (e.g., Tornatore et al., 2022; Reddy et al., 2023). In contrast, the "human element", particularly the readiness of Maritime Education and Training (MET), has received limited attention. Current training frameworks, primarily based on the International Convention on Standards of Training, Certification, and Watchkeeping for Seafarers (STCW) and the International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) (Choi and Lim, 2025), are largely shaped by legacy fuels such as Liquefied Natural Gas (LNG) and may not adequately address the distinct risk profiles of hydrogen and ammonia.

This study aims to address this gap by conducting a Systematic Literature Review (SLR) combined with bibliometric and thematic analyses to examine the current research landscape. Based on the identified mismatch between technological advancement and MET readiness, this study develops a conceptual "Future-Ready" competency matrix that links human-related operational risks to targeted training requirements. In doing so, this study contributes to bridging the safety gap between emerging fuel technologies and workforce preparedness.

2. Systematic Literature Review and Bibliometric Analysis

2.1. Systematic Literature Review

The SLR was conducted to examine safety challenges and training requirements associated with hydrogen (also green hydrogen) and ammonia in the maritime industry. To ensure transparency and reproducibility, the PRISMA framework was adopted (Page et al., 2021), providing a systematic procedure for study selection and reducing potential bias (Drucker et al., 2016).

The search strategy was designed to retrieve studies addressing operational risks, human factors, and training needs related to hydrogen and ammonia applications in the maritime sector. The query incorporated keywords, Boolean operators, and truncation symbols to ensure comprehensive coverage (Figure 1), including wildcard terms such as competenc* and train*.

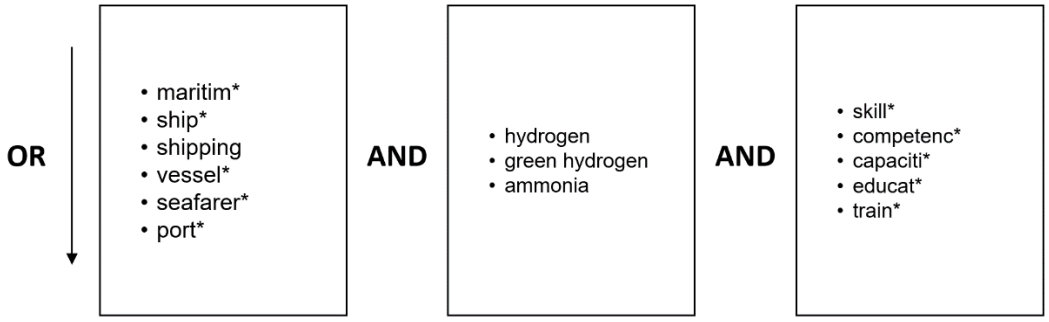


Figure 1. Keywords set for the literature search.

An initial screening of titles, abstracts, and keywords removed irrelevant studies, followed by full-text evaluation against predefined inclusion criteria focused on safety challenges, human factors, and MET requirements.

Studies published from 2016 onwards were included to capture the evolution of research over the past decade and support bibliometric analysis. The search was conducted using the Web of Science database. Following screening, 34 studies were selected (Figure 2), representing literature aligned with the study objectives.

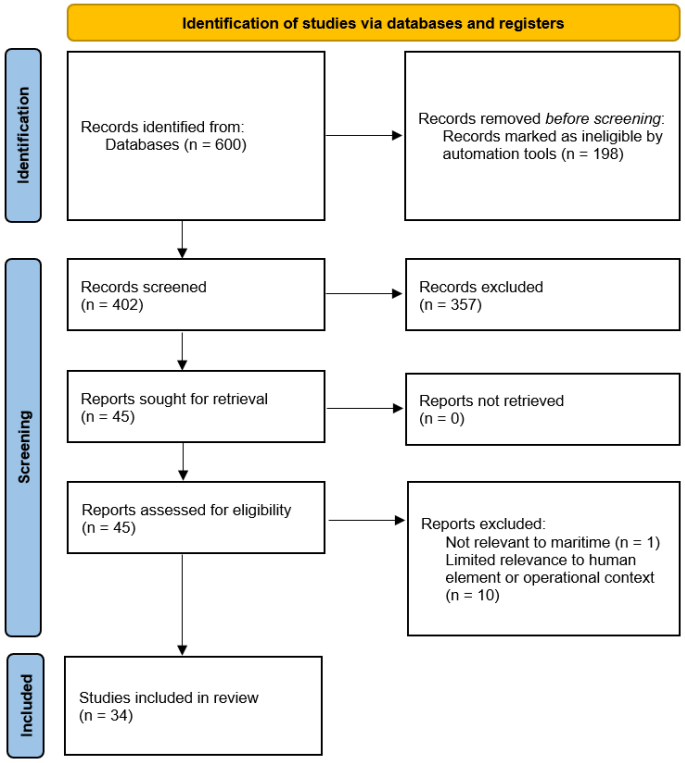


Figure 2. PRISMA flow chart for the selection process.

2.2. Bibliometric Analysis

A bibliometric analysis was conducted to examine the evolution of research on hydrogen and ammonia in the maritime field. Bibliometric methods enable a quantitative assessment of publication trends within a research domain (Aria and Cuccurullo, 2017).

The analysis was performed using the Bibliometrix package in R, based on 34 peer-reviewed publications identified through the review process. As shown in Figure 3, research activity has increased markedly since 2019, indicating growing academic interest in hydrogen and ammonia within the maritime sector. This trend highlights the rapid expansion of the field in recent years.

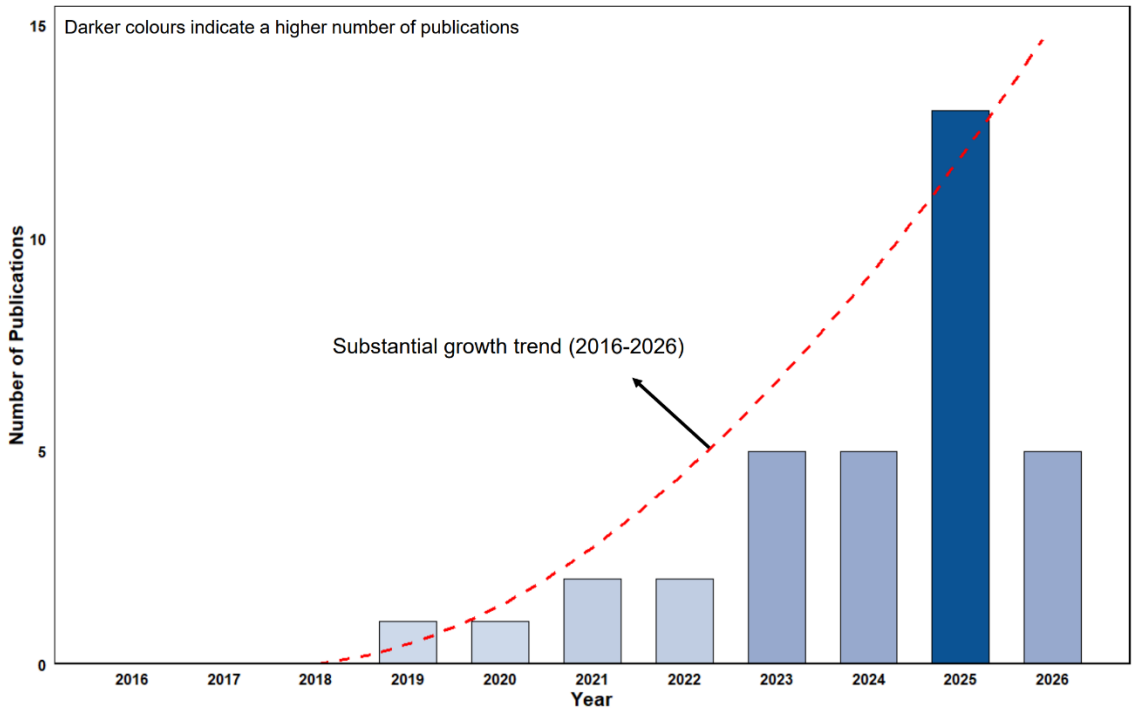


Figure 3. Academic publication trends.

2.3. Thematic Analysis

The thematic analysis was conducted to identify dominant research themes and assess the extent to which human-related and MET aspects are addressed. The results indicate a strong concentration on technology-driven themes, with limited attention to human-centred dimensions. As shown in Figure 4, the literature is dominated by a central "hydrogen" cluster, closely linked with terms such as ammonia, decarbonisation, and fuel cells, highlighting a focus on alternative fuel technologies. Additional clusters, including technologies and storage, further reflect research on system design, propulsion, and fuel handling.

Although a risk assessment cluster is present, its relatively low prominence suggests that safety research remains limited and primarily framed from a technical perspective. Notably, MET-related concepts, such as training, competence, and human factors, are largely absent. This indicates that the current literature is heavily skewed towards technological development, with insufficient attention to workforce preparedness. Overall, the findings reveal a clear imbalance between rapid technological advancement and limited MET-related research, forming the basis for the subsequent analysis of human-related operational risks and training gaps.

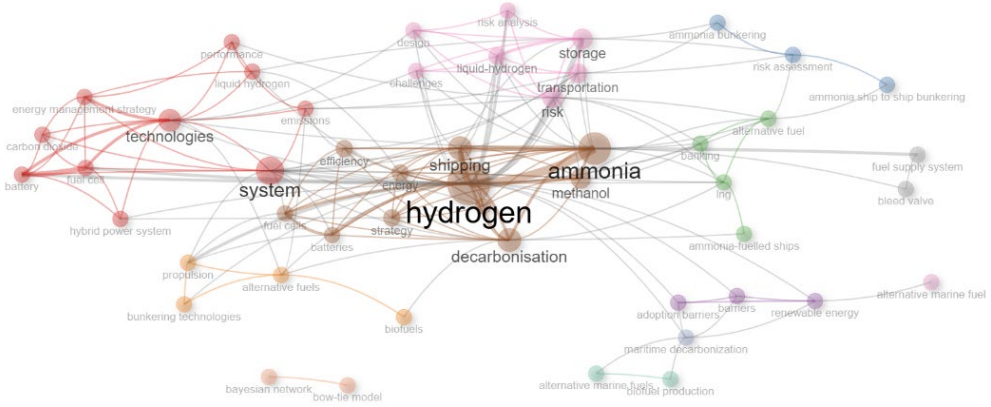


Figure 4. Thematic clusters of hydrogen and ammonia research.

3. Development of a Future-Ready MET Competency Matrix

3.1. Human-related Operational Risks

The transition to hydrogen and ammonia introduces complex safety challenges in maritime operations. These fuels exhibit distinct hazard characteristics, including high flammability for hydrogen (Fetimi et al., 2025) and acute toxicity for ammonia (Kojima, 2024), requiring careful handling and rapid response.

This study focuses on human-related failure events due to their direct relevance to training and competency development. Previous studies (e.g., Shi et al., 2023; Venkadasalam, 2023) highlight the critical role of human factors, with insufficient training, procedural non-compliance, and inadequate system understanding identified as key contributors to incidents.

Table 1. Human-related operational risk events in hydrogen and ammonia systems.

Alternative fuel	Human-related factors	
Hydrogen	・Lack of knowledge	・Lack of education
	・Lack of procedures	・Negligence
	・Oversight	・Overconfidence
	・Lack of safety culture	・Lack of preventive maintenance
	・Improper filling procedures	・Incorrect hose connection
	・Maintenance operation faults	・Delayed detection of micro-leaks
	・Real-time communication failures	
Ammonia	・Insufficient training	・Operational errors
	・Improper operation	・Maintenance errors
	・Mishandling of equipment	・Lack of adherence to procedures
	・Inadequate maintenance and inspection	・Lack of system understanding
	・Failure to recognise early leakage signs	・Improper assembly

・Late detection of leaks	・Failure to detect wear or damage
・Incorrect valve actuation	・Incorrect valve or pump operation
・Insufficient operator training	・Insufficient familiarisation

Source: Zincir and Zincir (2026; ammonia) and Inal and Senol (2026; hydrogen)

As summarised in Table 1, hydrogen and ammonia systems involve a wide range of human-related failure events, closely linked to increasing system complexity. These technologies require seafarers to operate unfamiliar systems and respond effectively to abnormal conditions. However, many remain insufficiently prepared, resulting in increased operational risks and operational inefficiencies. Overall, human-related factors represent a critical source of risk, directly linking system safety to crew competency and training.

3.2. Gaps in Current MET

Despite the importance of human-related factors, existing MET frameworks remain insufficiently aligned with hydrogen and ammonia systems (Torky et al., 2025). A clear mismatch exists between system safety demands and current training capabilities. While frameworks such as the STCW Convention and IGF Code provide a general foundation, they are largely based on LNG practices and do not fully address emerging fuel-specific challenges (Zincir, 2025).

A key gap is the lack of fuel-specific training. Hydrogen and ammonia introduce distinct risk profiles, including flammability, toxicity, and complex system behaviour (Kojima, 2024; Fetimi et al., 2025), which are not adequately covered in current curricula. Practical competence is also limited. Although awareness is increasing, seafarers often lack confidence in operating these systems due to insufficient hands-on training (Torky et al., 2025).

Further gaps include deficiencies in procedural training and safety culture, with issues such as non-compliance, improper handling, and delayed fault detection indicating limited emphasis on situational awareness and decision-making (Chen et al., 2024; Inal and Senol, 2026). Training at the ship–port interface is another limitation. Safe fuel handling requires coordinated vessel and port operations, yet current frameworks remain largely ship-centric (Chen et al., 2023).

Finally, training development has lagged behind technological progress. Although initiatives by IMO and World Maritime University (WMU) show growing awareness (WMU, 2024; IMO, 2025), efforts remain fragmented. Overall, current MET frameworks are not fully equipped to support safe implementation, highlighting the need for fuel-specific, risk-informed competency development.

3.3. Framework Development

Based on the identified risk factors and gaps, this study proposes a conceptual “Future-Ready” competency matrix for hydrogen and ammonia operations. The framework translates human-related operational risk factors into specific competency requirements, directly linking operational hazards with training needs. It is structured around three core dimensions: knowledge, practical skills, and simulator-based training, aligned with competency-based education principles and STCW requirements (ITF, 2017).

Given the complexity of hydrogen and ammonia systems, simulator-based training is incorporated as a critical dimension (Venkadasalam, 2023), as many failure events require scenario-based learning beyond theoretical instruction (Chen et al., 2024). Knowledge competencies focus on understanding fuel properties such as flammability, toxicity, and system behaviour. Practical skills emphasise safe operation, procedural compliance, and response to abnormal conditions. Simulator-based training supports experiential learning in high-risk scenarios, including fuel leakage and bunkering operations.

Table 2 presents the proposed matrix by mapping human-related failure events to corresponding competency requirements and training implications. This mapping demonstrates how identified risks can be systematically translated into targeted and practical training strategies.

Table 2. Conceptual “Future-Ready” competency matrix.

Risk categories	Representative human-related failure events	Required competencies	Training implications
Leakage and detection	・Delayed detection of micro-leaks ・Failure to recognise early leakage signs	・Hazard recognition ・Situational awareness	・Simulation-based leak scenarios

	・Late detection of leaks	・Leak identification capability	・Emergency response drills
Operational errors	・Operational errors ・Improper operation ・Improper filling procedures ・Improper assembly ・Incorrect hose connection ・Mishandling of equipment ・Lack of adherence to procedures ・Incorrect valve or pump operation ・Incorrect valve actuation ・Real-time communication failures	・Procedural compliance ・Operational accuracy ・Task execution	・Hands-on training ・Checklist-based exercises ・Bunkering simulations
Training and knowledge deficits	・Insufficient training ・Insufficient operator training ・Insufficient familiarisation ・Lack of knowledge ・Lack of education ・Lack of procedures ・Lack of system understanding	・Fuel-specific knowledge ・System understanding ・Procedural knowledge	・Updated MET curricula ・Fuel-specific modules
Maintenance-related failures	・Maintenance errors ・Inadequate maintenance and inspection ・Lack of preventive maintenance ・Maintenance operation faults ・Failure to detect wear or damage	・Maintenance competence ・Inspection skills ・Fault identification	・Maintenance training ・Inspection exercises
Behavioural factors	・Negligence ・Oversight ・Overconfidence ・Lack of safety culture	・Risk perception ・Decision-making ・Safety awareness	・Human factor training ・Scenario-based exercises

4. Discussion and Implications

The findings reveal a clear imbalance between rapid technological development and the limited consideration of human-related and training aspects. The bibliometric and thematic analyses demonstrate that current research is heavily concentrated on fuel technologies and system design, while MET-related topics remain largely absent.

This imbalance has important implications for maritime safety. Unlike conventional fuels, hydrogen and ammonia introduce fundamentally different hazard characteristics, requiring new forms of knowledge, operational skills, and decision-making capabilities. However, existing MET frameworks remain largely aligned with LNG-based training approaches, resulting in a mismatch between operational demands and crew competencies.

From an industry perspective, the results highlight the urgent for fuel-specific and risk-informed training frameworks. MET institutions must move beyond generalised safety training towards competency-based approaches that explicitly address hydrogen and ammonia systems. Shipping companies and operators should also prioritise simulator-based training to enhance practical readiness for high-risk scenarios.

From a regulatory perspective, the findings suggest that current international frameworks, including STCW and IGF Code, require further development to incorporate emerging fuel-specific competencies. Greater alignment between technological innovation and regulatory adaptation will be essential to ensure safe implementation.

Overall, this study emphasises that successful decarbonisation is not solely a technological challenge, but also a human and organisational one, requiring integrated development of systems, regulations, and competencies.

5. Conclusions

This study examined the readiness of MET in the context of green hydrogen and ammonia adoption through an SLR and bibliometric analysis. The results demonstrate that current research is strongly focused on technological development, with limited attention to human-related safety and training.

The analysis identifies a clear gap between the complexity of emerging fuel systems and the capabilities provided by existing MET frameworks. To address this, this study proposes a conceptual "Future-Ready" competency matrix that links human-related operational risks to knowledge, practical skills, and simulator-based training requirements.

The findings highlight the need for a shift towards fuel-specific, risk-informed, and competency-based training approaches. Bridging this gap will be critical to ensuring safe and effective implementation of hydrogen and ammonia fuels in the maritime sector.

Future research should focus on empirical validation of the proposed framework and its integration into international training standards and industry practices.

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Quantifying COLREG Restricted Visibility: A Fuzzy Set Approach Based on Expert Maritime Judgment

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Abstract: The International Regulations for Preventing Collisions at Sea (COLREG) have been corner stone of successful avoidance of collisions at sea for decades. These human-centered rules are abundant with vague and subjective terms. Reduced visibility environment, due to navigational situation uncertainty experienced by navigator, significantly elevates the risk of collision. Section III of the Rules and Rule 19 regulate conducts of vessels in the restricted visibility. Rule relies on visual observation, not on any measurable metric. This study addresses this problem by empirically quantifying the maritime experts' interpretation of reduced visibility. To model the ambiguity of the reduced visibility term, the methodology uses fuzzy set theory. Navigational experts were asked to define ranges of five linguistic values, which correspond to different grades of visibility. Responses are statistically analyzed to define the membership functions. Furthermore, possible differences between groups of respondents were evaluated by analysis of variance. The findings provide a quantified interpretation of reduced visibility as experienced by navigators. The research demonstrates that usage of fuzzy sets is a simple and efficient tool for quantifying COLREG terms. This work contributes to maritime safety by defining a significant collision risk variable by simple concept, enabling its direct applications to intelligent navigational solutions.

Keywords: Risk of Collision; MASS; Navigation; Collision avoidance

1. Introduction

Visibility is defined as the maximum horizontal distance at which objects can be seen and identified with the naked eye (National Geospatial-Intelligence Agency [NGA], 2019). In navigational practice, visibility is often estimated by using RADAR to measure the range of an object spotted on the horizon. Restricted visibility is an extremely hazardous condition at sea (Sasa et al., 2005; Shen et al., 2023), especially in high-traffic areas, and has been a significant contributing factor in many navigational accidents. According to Wang (2012), poor visibility significantly impacts maritime safety, contributing to more than 60% of ship collisions. One of the most prominent examples is the collision between the MV Stockholm and the Italian liner Andrea Doria, which occurred under conditions of poor visibility (Bell, 1971; Garzke and Simpson, 2012).

This danger is formally acknowledged in the International Regulations for Preventing Collisions at Sea (COLREG). Specifically, Rule 19 mandates that vessels exercise extra caution when navigating in restricted visibility, requiring them to proceed at a safe speed with engines ready for immediate maneuvering. However, COLREG does not precisely quantify the term "restricted visibility," leaving it as a vague or fuzzy concept. This research recognizes this gap and aims to clearly define this COLREG linguistic term. According to COLREG, restricted visibility refers to any condition in which visibility is restricted by fog, mist, snow, heavy rainstorms, sandstorms, or other similar causes (International Maritime Organization [IMO], 1972).

Fog is a primary cause of restricted visibility at sea. It consists of a ground-level cloud of water droplets formed when air cools to its dew point. Two common types include radiation fog, resulting from the cooling of land surfaces overnight, and advection fog, which forms when warm, moist air moves across a colder sea surface (NGA, 2019). Beside fog, the rainstorm presents a particularly dangerous condition, as even RADAR echoes of surrounding objects can become unreliable within area of heavy rain. Salinas (2006) identified controversies

regarding Rule 19, particularly concerning correct maneuvering in accordance with paragraph (d), and proposed COLREG amendments to clarify the conduct of vessels. This research quantifies navigators' perception of restricted visibility, which is described in practice through linguistic variables. The most common variables used are Very poor, Poor, Moderate, Good, and sometimes Very good; therefore, this paper adopts the same linguistic values.

2. Previous research

Scientific research on the risk of collision at sea has rarely considered environmental parameters such as visibility, although these are major factors affecting mariners' judgment of navigational risk (Öztürk and Cicek, 2019). In an analysis of 27 maritime collisions, Chauvin et al. (2013) identified limited visibility as one of the key environmental factors. While visibility is recognized by navigational experts as a paramount factor in risk evaluation (Kristić et al., 2025), it is not frequently used in collision risk modeling. Wang et al. (2023a) studied the impacts of Arctic sea fog on route planning and navigational efficiency, defining foggy days as those with visibility of less than 1 km. Furthermore, Ding et al. (2024) state that conditions limiting visibility to less than 4 km are referred to as "poor visibility." Another study by Wang et al. (2023b) constructed a dataset for fog classification, as presented in Table 1.

Table 1. Visibility rating table as proposed by Wang et al. (2023b)

Visibility scale	Perceived distance in nautical miles	Weather condition
0	Less than 0.05	
1	0.05-0.1	Heavy fog
2	0.1-0.25	Dense fog
3	0.25-0.5	Fog, light fog
4	0.5-1	Mist
5	1-2	Moderate rain, light fog
6	2-5	Light rain, light fog
7	Greater than 5	No fog

According to the World Meteorological Organization (WMO, 2012), descriptive terms for visibility correspond to distances in nautical miles, similar to the descriptive scale used by the International Maritime Organization (IMO, 2021), as displayed in Table 2.

Table 2. Descriptive terms for visibility as set by IMO (2021) and WMO (2012)

Descriptive terms for visibility	(IMO, 2021) Nautical miles	WMO (2012) Nautical miles
Very poor	Less than 0.5	Less than 0.5
Poor	0.5 - 2	0.5 - 2
Moderate	2-5	2-5
Good	5-25	Greater than 5
Very good	More or equal to 25	N/A
Unknown		N/A

It could be noted that all proposed descriptive terms are described by crisp values, meaning that if poor visibility is 2NM, then when visibility is 2.1NM, it would be a moderate visibility. This reasoning is contrary to human understanding of nature, where there is a smooth transition between categories. This transition is easily described by fuzzy sets, which will be used in this paper.

3. Methodology

This paper is part of an extensive study on collision risk conducted from September 2021 to April 2023. The study utilized an online questionnaire distributed internationally to 220 navigation experts. Approved by the University of Dubrovnik Ethics Committee, the survey included Participant Profile Questions (PPQ) and

Range of Fuzzy Variables Questions (RFVQ). The latter employed a custom questionnaire tool to define the shape and range of linguistic variables. Fuzzy set theory (Zadeh, 1965) models linguistic variables used in everyday communication, where elements have a degree of membership between 0 and 1, in contrast to classical "crisp" sets with binary membership. Vague term safe speed could be modeled by usage of crisp and fuzzy set, but as in example, transition between safe and unsafe in gradual within fuzzy theory (Figure 1).

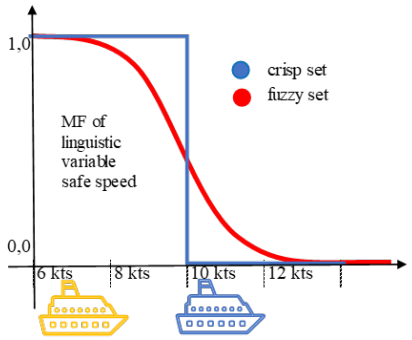


Figure 1. An example of fuzzy and crisp set safe speed

The membership functions commonly utilized in scientific research are Gaussian, triangular, and trapezoidal. This study uses Gaussian membership functions to describe fuzzy sets. Gaussian membership functions are selected as they effectively characterize the central tendency of the fuzzy set and capture uncertainty inherent in expert assessments. This research used a customized horizontal method where experts defined crisp intervals for linguistic values using a double-slider (Kristić and Žuškin, 2024). Respondents used a dual-slider interface to specify the minimum and maximum boundaries of each linguistic variable, with every variable assessed on its own dedicated slider. Values were expressed in nautical miles, across a range from 0 to 25 nautical miles, with the slider's precision set at 0.1 nautical miles. Five values (Very poor, Poor, Moderate, Good, and Very good) were used to provide greater detail across the linguistic variable. The collected data modeled expert judgment, capturing consensus and variability in experts opinion.

4. Results

This section presents the questionnaire findings, beginning with the results describing the demographics and professional backgrounds of the participating navigation experts. The subsequent subsection provides descriptive statistics for the linguistic variable which is used to create corresponding membership functions.

4.1. Respondent Demographics and Professional Background

An online questionnaire was distributed to active navigational experts. A total of 220 active maritime professionals took part in this study (Figure 2). of 113 Masters, 65 Chief Officers, 28 Second Officers, and 14 Third Officers. Masters formed the largest cohort, representing 51% of the respondents, followed by Chief Officers at 30%. The years of professional experience reported by the participants aligned closely with their rank distribution. The most seasoned participants, with over 15 years of experience, constituted the largest segment at 58.2%. Those with 10 to 15 years of experience made up 16.3% of the sample, while respondents with 5 to 10 years accounted for 15.5%. Officers with 3 to 5 years of experience represented 4.5%, and finally, those with 1 to 3 years of experience comprised 0.5% of the total.

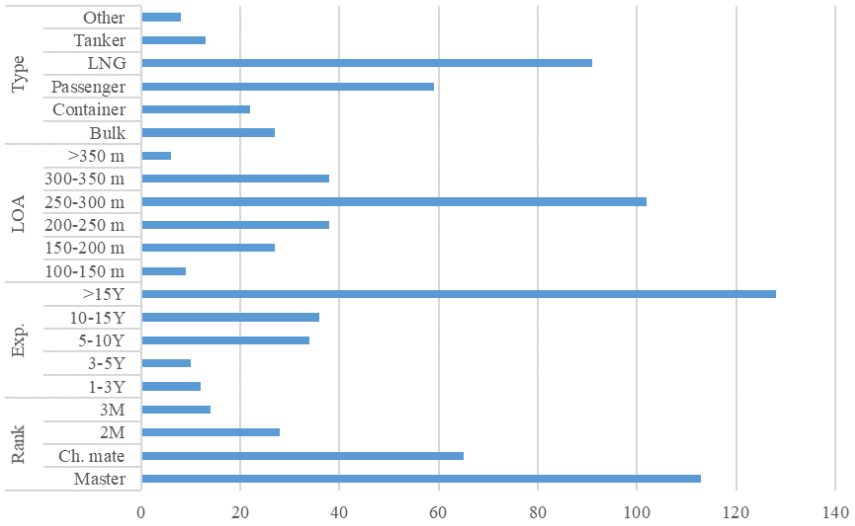


Figure 2. General share of respondents

4.2. Fuzzy variable Visibility

A second set of results was used to establish fuzzy sets for the linguistic variables, thereby enabling the quantitative interpretation of COLREG-related terminology. Since the survey responses defined the linguistic variable's range by minimum and maximum value, we discretized the continuous domain using the slider's 0.1 NM precision step. Statistical analysis of the collected data was used to model expert judgment for visibility terms (Very poor, Poor, Medium, Good, Very good). The results of the statistical analysis of the second group of questions (RFVQ), which served to specify the linguistic variable and associated linguistic values, are summarized in Table 3, where SD denotes standard deviation, Mean represents the arithmetic mean, and C indicates the median.

Table 3. Results of statistical analysis of second group of questions

Fuzzy values	SD	Mean	Median
Very Poor (VP)	0.7241	0.9306	0.8
Poor (P)	1.3644	2.8451	2.7
Moderate(M)	2.4005	6.4940	6.3
Good (G)	3.9328	12.2142	12.2
Very Good (VG)	3.7468	19.5070	20

The results reveal that the arithmetic mean value for Poor visibility is approximately 2.8 NM, which is somewhat stricter than the commonly accepted definition. These statistically obtained arithmetic mean and standard deviation, as presented in Table 3, were subsequently employed to construct membership functions (Figure 3). The membership functions were formulated using Gaussian curves, whose parameters were derived from the empirical distribution of expert responses, specifically the mean and standard deviation assigned to each linguistic variable.

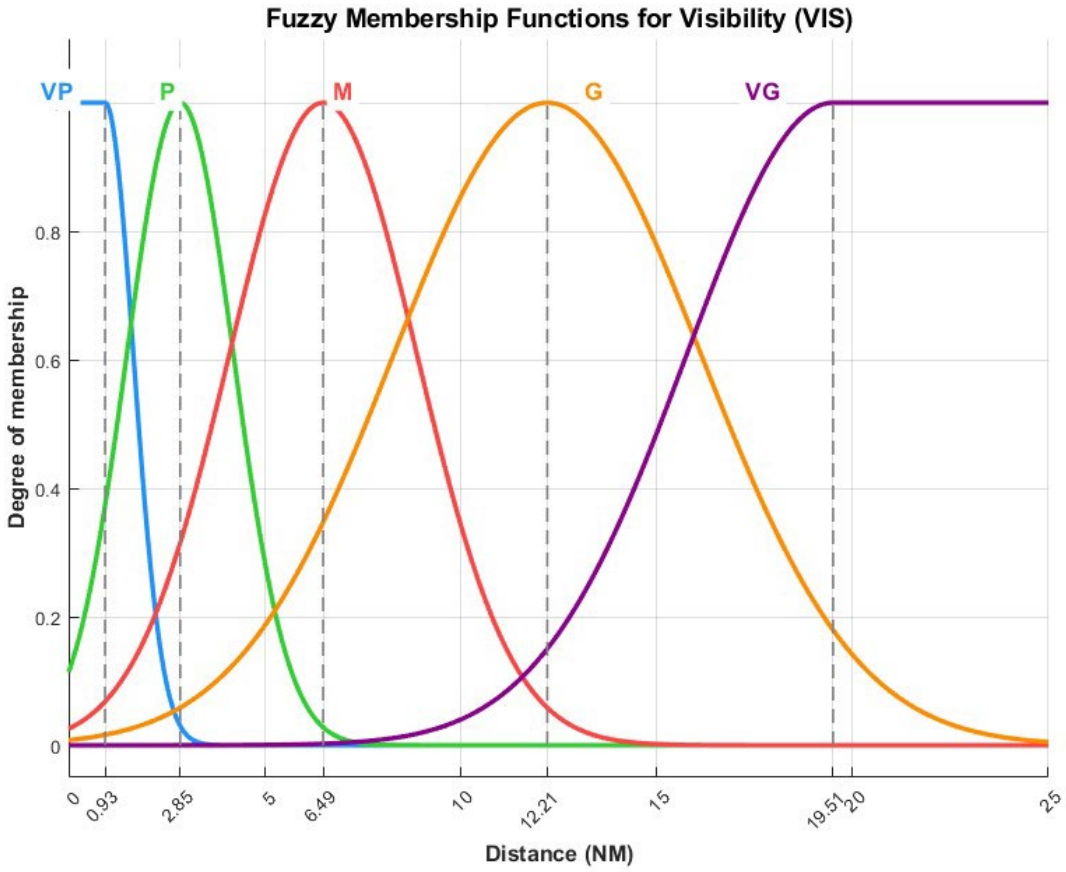


Figure 3. Gaussian membership functions

The resulting membership functions reveal no overlap between the cores of the fuzzy sets. Furthermore, the functions are more densely distributed in the lower range, where very poor, poor and moderate values are distributed.

5. Discussion and Conclusion

The findings of this study present that maritime experts knowledge could be easily quantifiable by usage of fuzzy sets, despite the inherent vagueness of COLREG terminology. While common definition of poor visibility is anything below 2 NM, the statistical analysis of expert responses reveals that maritime professionals find that value stricter (Mean = 2.8NM, Median=2.7NM). This finding could be related to relatively higher speed of modern vessels, requiring larger distance to perform evasive maneuver. Furthermore, dense grouping of membership functions for linguistic values moderate and below, could indicate that experts consider this as more important as expected. While the study provides a valuable quantification of expert judgment, there are limitations which should be acknowledged. Although the survey included 220 active maritime professionals, the majority were Masters and Chief Officers. Also, there is a great number of experts sailing at LNG carriers. This could also contribute to stricter perception of restricted visibility, as these vessels are known by increased safety culture. Presented fuzzy membership functions provide an effective and simple representation of expert reasoning. This enables integration of these membership functions into collision avoidance system and decision supports systems. By converting linguistic values into mathematically defined membership functions, the study bridges the gap between human orientated rules and machine logic. The resulting models improves the modeling of collision risk variables and support the development of intelligent navigational solutions, particularly for Maritime Autonomous Surface Ships (MASS). As the maritime industry moves toward increasing automation,

the ability to translate mariner's perception into computable variables will be essential for ensuring safe and compliant sailing.

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A Study on Non-Contact Surface Tension Measurement Using Vibration Analysis of Acoustically Levitated Droplets

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Abstract: Conventional surface tension measurement methods (e.g., Wilhelmy plate method, ring method, pendant drop method) involve physical contact between the sample and measuring apparatus, potentially causing measurement errors due to contamination or thermal conductivity effects. To avoid this, we attempted to measure surface tension by levitating the sample in air using acoustic levitation. A sweeping acoustic signal was used to induce oscillation in the levitated droplet, and the resonance frequency was identified. Based on this frequency, the surface tension was calculated using Rayleigh's equation. This method minimizes the influence of wettability and contamination and is thus considered effective for measuring surface tension, a critical physical property in simulations of processes such as fuel injection and lubrication in piston-cylinder systems. The droplet shape changed irregularly under the sweeping acoustic waves generated by the speaker. Among these changes, frequencies at which the deformation appeared relatively gradual showed good agreement with the resonance frequencies predicted by Rayleigh's equation. These results demonstrate the feasibility of non-contact surface tension measurement using small-volume droplets.

Keywords: micro droplet; surface tension oscillation; acoustic levitation; resonance frequency

1. Introduction

Accurately measuring the surface tension of liquid droplets improves the precision of combustion simulations in marine engine design, contributing to fuel spray optimization, reduction of unburned fuel, and evaluation of alternative fuels (Zhou et al., 2017; Chhetri and Watts, 2013). Generally, surface tension is measured with the sample in contact with a container or substrate. In the Wilhelmy method, surface tension is derived from the force required to pull a plate from the liquid surface; in the ring method, it is derived from the force at which a membrane between a ring and the liquid surface breaks; and in the pendant drop method, it is calculated based on the maximum diameter of a droplet suspended from a needle: in the maximum bubble pressure method, it is determined from the maximum pressure required to form a bubble at the tip of a capillary immersed in the liquid. However, all these methods involve contact between the sample and the apparatus, introducing possible error due to surface contamination or roughness. Equipment cleaning and drying are also time-consuming. For these reasons, a non-contact measurement technique that eliminates physical contact between the sample and the apparatus is highly desirable.

Therefore, this study focuses on acoustic levitation—a technique for spatially trapping droplets in free space without physical contact. Because this technique suspends microdroplets without mechanical interaction, it is applicable as a non-contact method for analyzing physical properties.

Contact-free surface tension measurement using acoustic levitation has been explored through several approaches. A photodiode-based detection of free droplet oscillations has been used to infer surface tension (Arcenegui-Troya et al., 2019), while machine-learning-based approaches that predict surface tension from droplet contours have also been reported, achieving high accuracy even for large deformations (Argyri et al., 2023). However, these approaches require either a dedicated optical detection system or extensive training datasets and a complex neural-network-based data-processing pipeline. In contrast, the present study determines surface tension using only a conventional camera and a frequency-sweeping procedure, without the need for

specialized detection systems or machine-learning models, by directly identifying the resonance frequency based on Rayleigh's theoretical framework.

2. Surface tension oscillation

When a microdroplet deviates from a spherical shape, it undergoes vibrational deformation due to surface tension forces. The relationship between the surface tension and the vibrational frequency of such oscillations is described by the Rayleigh equation (1) (Rayleigh, 1897; Prosperetti, 1977):

$$f = \frac{1}{2\pi}\sqrt{\frac{\gamma n(n-1)(n+2)}{\rho r^3}} \tag{1}$$

f: resonance frequency [Hz], γ: surface tension [N/m], ρ : density [kg/m³], r: droplet radius [m], n: oscillation mode.

A droplet levitated in air undergoes deformation and oscillation according to oscillation modes governed by surface tension.

By rearranging Equation (1), the surface tension for the second oscillation mode (n = 2) can be calculated using Equation (2) shown below. In this study, we aimed to determine the resonance frequency of acoustically levitated droplets by sweeping the acoustic excitation frequency and then calculate the surface tension using equation (2).

$$\gamma = \frac{\pi^2}{2}\,\rho r^3 f^2 \tag{2}$$

3. Experimental Methods

Figure 1 shows the schematic diagram of the experimental setup. The levitation device traps micro-objects in the nodes of standing waves generated by multiple ultrasonic emitters (Marzo et al., 2017). In our setup, a microdroplet is gently dispensed using a micropipette into the standing wave node, enabling spatial suspension. A speaker (SPL Limited) was placed adjacent to the droplet to emit acoustic waves.

The speaker was driven by a function generator (NF Corporation, WAVE FACTORY 1941), allowing precise frequency control. To capture droplet oscillations, a telecentric lens (Optart, MP-2M-110-2M) and a camera (IDS, UI-3160CP-M-GL R2.1) were positioned directly in front of the droplet, with a backlight and diffusion plate to obtain a shadow graph image. Figure 2 shows the photograph of the acoustic levitation device and the speaker

The experimental procedure was as follows: a microdroplet was levitated at the node of a standing wave. Acoustic waves were emitted from the side speaker, with frequencies swept around the theoretical resonance frequency calculated using literature surface tension values. The excitation frequency was swept from 10% below to 10% above the resonance frequency, with each frequency applied for 3 seconds in 0.1 Hz increments. For example, for a 3 μL hexadecane droplet (surface tension 27.5 mN/m at 25 °C; John et al., 2017), the resonance frequency is 99 Hz, so the sweep range was set from 79 Hz to 119 Hz. The camera captured droplet oscillation at a low frame rate (10 fps) and long exposure time (2 ms). Image processing was used to extract changes in the projected area of the droplet.

The resonance frequency was identified as the frequency at which the projected area showed maximal variation, and surface tension was calculated using Rayleigh's equation (2).

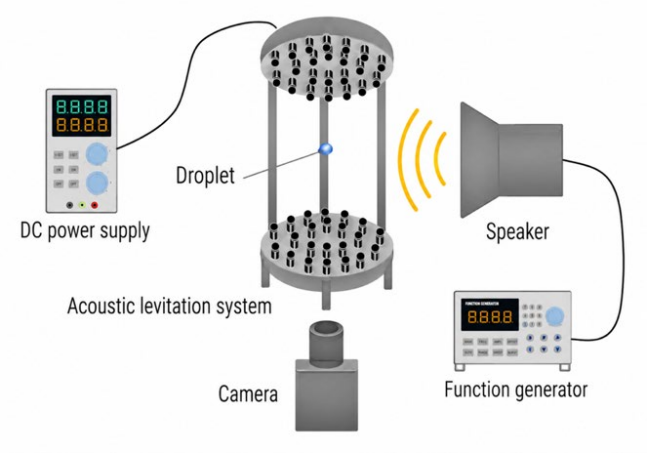


Figure 1 Schematic diagram of the experimental setup

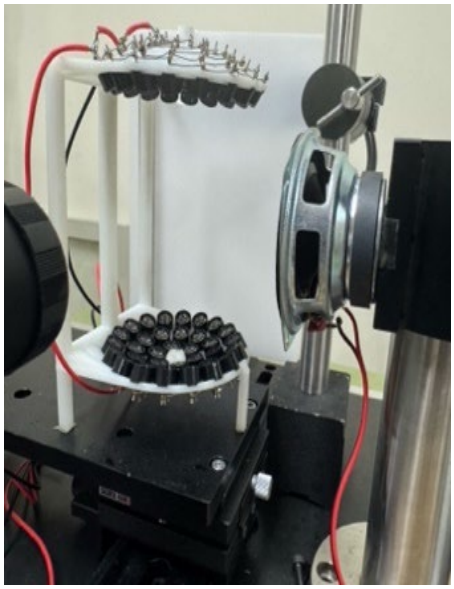


Figure 2 Acoustic levitation device.

4. Results

Figure 3 shows the experimental results for a 3 μL hexadecane droplet. The horizontal axis represents time, while the left and right vertical axes represent the aspect ratio of the droplet (width divided by height) and the sweeping frequency, respectively. After the acoustic excitation began, the aspect ratio appeared to fluctuate randomly; however, several regions were observed where the change in aspect ratio became relatively gradual. These points are indicated by arrows as (a), (b), and (c). Similar features were observed in all three trials, indicating good reproducibility. In this study, the resonance frequency was defined as the frequency at which the droplet deformation transitioned from large-amplitude oscillation to a relatively gradual change (point b in Figure 3).

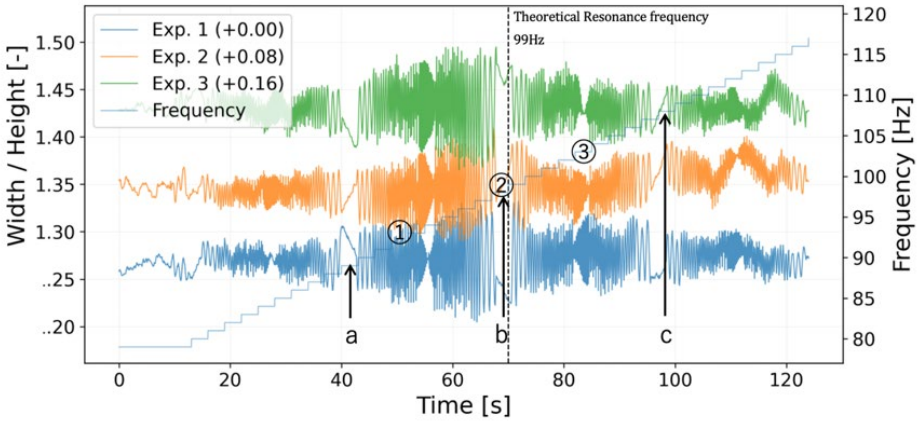


Figure 3 Transition of width-to-height ratio and resonance frequency of a 3 µL hexadecane droplet exposed to a sweeping sound wave.

Figure 4 shows superimposed images created from ten consecutive droplet images taken at the points (①, ②, ③) in Figure 3. At the non-resonant points (① and ③), almost no visible difference was observed among the droplet images. In contrast, at point ②, which was near resonance, deformation in both the horizontal and vertical directions was observed.

The resonance frequencies at the three points where the change in aspect ratio became relatively gradual, namely points (a), (b), and (c), were 88 Hz, 98 Hz, and 106 Hz, respectively. Assuming the droplet to be spherical with a radius of 0.89 mm, the surface tension values calculated using Equation (2) were 21.1 mN/m, 26.1 mN/m, and 30.6 mN/m.

Among these points, particular attention was paid to point (b), where the large-amplitude deformation transitioned to a relatively gradual change and was followed by smaller deformation. At this point, the resonance frequency was 98 Hz, and the calculated surface tension was 26.1 mN/m, showing good agreement with the literature value of 27.5 mN/m at 25 °C (John et al., 2017).

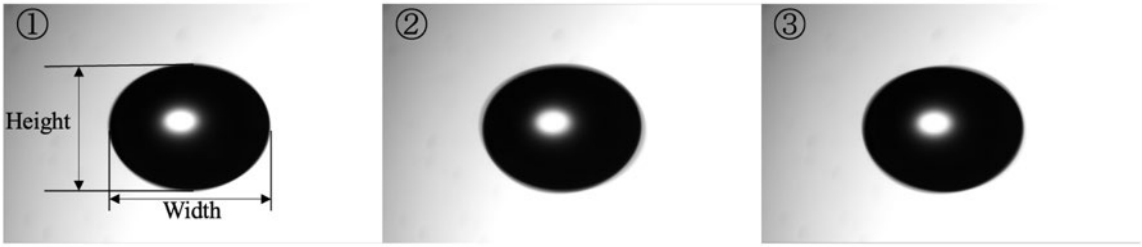


Figure 4 Snapshots of a 3 µL hexadecane droplet exposed to sound waves at various frequencies. Alphabetical letters indicate the points in time shown by the arrows in Figure 3.

Figures 5 and 6 show similar results for hexadecane droplets with different volumes (2, 3, 4, 5, 6, and 7 µL). In Figure 5, the horizontal axis represents droplet volume, while the vertical axis represents frequency. Frequencies corresponding to points where the change in droplet deformation became relatively gradual are indicated by circles. As described above, the square symbols represent the frequencies at which the large-amplitude deformation transitioned to a relatively gradual change. In particular, the resonance frequencies indicated by the square symbols showed good agreement with the theoretical predictions for the n = 2 oscillation mode.

Figure 6 shows the surface tension values calculated from the frequencies indicated by the square symbols. Although slight variations were observed, the calculated surface tension values for all droplet volumes were generally consistent with the literature value.

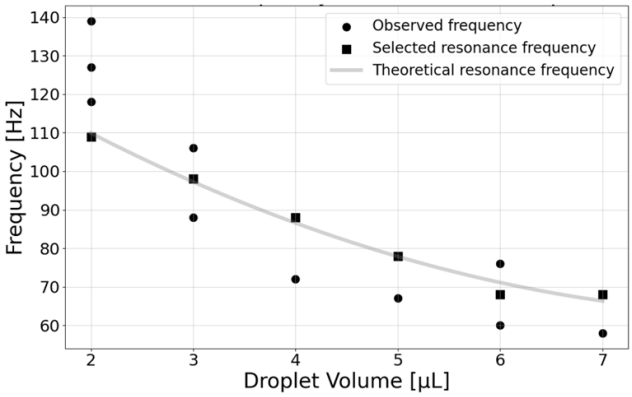


Figure 5 Resonance frequency of hexadecane droplets.

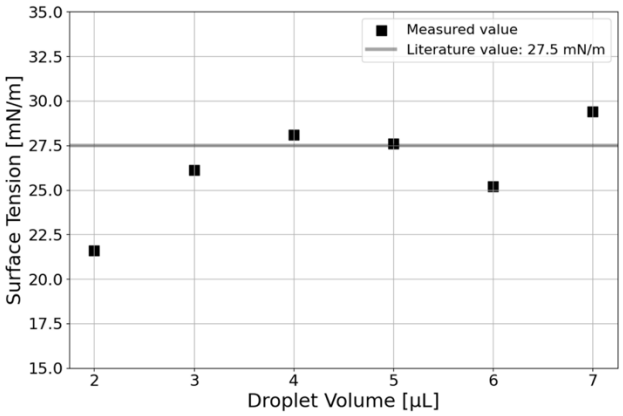


Figure 6 Measured surface tension of hexadecane droplets.

Using the same method, experiments were also conducted for tetradecane and silicone oil (KF-96, 10 cSt) with a droplet volume of 3 µL. As shown in Figure 7, all measured values were within ±10% of the corresponding literature values (John et al., 2017; Shin-Etsu Chemical, n.d.). Although some differences from the literature values were observed, the results demonstrate that surface tension can be estimated from droplet oscillation behaviour.

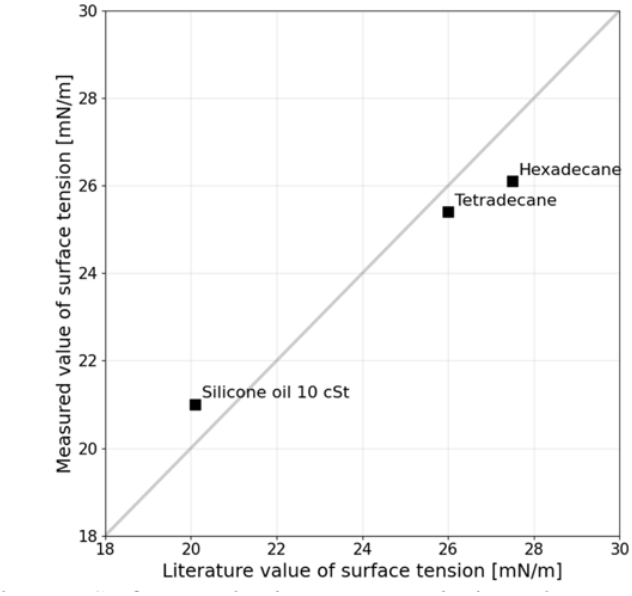


Figure 7 Surface tension by present method vs. literature value.

5. Discussion

As shown in Figure 3, instead of a single clear resonance peak, several candidate points can be observed at which the change in aspect ratio becomes more gradual. Among these, the point showing the clearest transition to such a gradual change was selected as the resonance frequency, and this gave good agreement with the literature value. However, it is not easy to identify which of these candidate points corresponds to the true resonance. At least two mechanisms can be considered as reasons why multiple candidate points appear. One is amplitude-dependent excitation of non-axisymmetric modes and internal circulation (Ansari Hosseinzadeh and Holt, 2017). The other is static distortion of the droplet shape caused by the levitation field itself, as suggested by analogy with magnetically levitated droplets (Cummings and Blackburn, 1991). However, this latter framework cannot be directly applied to the present case. Because these two mechanisms may act at the same time, it is difficult to rule out the resulting multiplicity of candidate points, and it is equally difficult to remove the underlying nonlinear effects themselves.

Even considering these issues, the measurement accuracy obtained in this study is somewhat lower than the accuracy reported for more advanced methods. For example, a machine-learning-based analysis of acoustically levitated droplets has achieved a relative error of about 3% (Argyri et al., 2023). However, this method requires a large training dataset, and another study used a dedicated multi-transmitter levitation system with optical detection (Arcenegui-Troya et al., 2019). In contrast, the present study achieved a reasonable accuracy (within ±10%) using a relatively simple experimental setup and Rayleigh's equation alone, without machine learning or specialized optical equipment.

Surface tension is a fundamental physical property that governs droplet size, evaporation behaviour, and the uniformity of atomization and mixing during fuel spraying. Since marine engines use heavy fuel oil whose properties vary considerably, the accuracy of this value directly affects the predictive accuracy of combustion simulations, and in turn the optimization of fuel injection and the reliability of emission assessments. The non-contact method proposed in this study can obtain such fuel property data without these limitations, which is of practical value.

6. Conclusion

In this study, a non-contact surface tension measurement method using acoustic levitation was investigated. By applying sweeping acoustic waves to levitated droplets, the resonance frequencies of droplet oscillation were identified, and the surface tension was calculated using Rayleigh’s equation. For hexadecane droplets with different volumes, the obtained resonance frequencies showed good agreement with the theoretical predictions for the n = 2 oscillation mode, and the calculated surface tension values were generally consistent with the

literature values. Similar results were also obtained for tetradecane and silicone oil. These results demonstrate the feasibility of non-contact surface tension measurement for microdroplets using acoustic levitation.

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Securing the Seas: Privacy-Enhancing Technologies and Human-Machine Interaction in Maritime Cloud Environments

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Abstract: Rapid maritime digitalisation has created a profound dependence on cloud infrastructures, introducing significant cybersecurity and jurisdictional risks within a weakly harmonised regulatory environment. This paper evaluates the intersection of cyber risk, training gaps and human-machine interaction through a legal-technical review and an empirical survey of 40 maritime professionals. Findings reveal a systemic reliance on digital interfaces, with 87.5% of respondents anticipating critical delays in detecting data manipulation during open-sea transit. Corroborated by behavioural insights from eye-tracking research, these results suggest that automation complacency and cognitive tunnelling render human monitoring an insufficient fail-safe in paperless environments. Consequently, Privacy-Enhancing Technologies (PETs) and federated architectures emerge as a promising design direction for future privacy-preserving verification frameworks. Ultimately, this study maps current vulnerabilities and offers a socio-technical roadmap for enhancing maritime resilience in an increasingly automated global supply chain.

Keywords: Maritime Cybersecurity; Cloud Computing; Privacy-Enhancing Technologies; Human-Machine Interaction; Maritime Education and Training

1. Introduction

The maritime sector's digital transformation integrates advanced navigational systems, such as Electronic Chart Display and Information Systems (ECDIS), Global Navigation Satellite Systems (GNSS) and Automatic Identification Systems (AIS), into continuous vessel-to-shore data networks. Structurally, this is modelled as a four-layer cyber-physical system:

$$\boldsymbol{L} = \{\boldsymbol{l}_{\{perceptual\}}, \boldsymbol{l}_{\{network\}}, \boldsymbol{l}_{\{cloud\}}, \boldsymbol{l}_{\{application\}}\}$$

Within this framework, the perceptual layer handles raw sensor data, while the network and cloud layers manage the transmission and centralised processing that fuel modern maritime applications (Surucu-Balci et al., 2024; Wimpenny et al., 2022). However, vulnerabilities across these layers risk remote cyberattacks, threatening maritime safety and supply chains. While Artificial Intelligence (AI) and Intrusion Detection Systems (IDS) improve threat detection, they add complexity and rely on large, sensitive datasets (Iphar et al., 2020). This technical evolution faces a fragmented regulatory landscape, juxtaposing the European General Data Protection Regulation (GDPR) with non-binding International Maritime Organization (IMO) guidelines and inconsistent US data laws. As autonomous vessels expand the cyber threat landscape, this paper evaluates whether Privacy-Enhancing Technologies (PETs), like homomorphic encryption and federated learning, can provide the necessary security architecture while mitigating jurisdictional friction.

2. State of the Art: Legal, Socio-Operational and Technical Frameworks

Maritime data governance in cloud-enabled environments is hindered by regulatory fragmentation and jurisdictional ambiguity. A critical gap exists between horizontal privacy frameworks like the GDPR and sector-

specific global standards from the IMO. While the GDPR mandates strict data confidentiality and Personally Identifiable Information (PII) protection, the IMO's cyber risk management guidelines (e.g., Resolution MSC.428(98)) prioritize operational safety and the integrity of Operational Technology (OT) to prevent physical accidents (Triggiano and Romanini, 2025). Shipowners must thus satisfy terrestrial IT privacy laws and maritime OT safety standards without a unified compliance framework. Furthermore, in the US, state-level regulations like the California Consumer Privacy Act (CCPA) alongside federal inconsistencies (Chintoh et al., 2025) create a *dual-layer* jurisdictional problem. Consequently, a critical concern identified by stakeholders, particularly within the European Marine Observation and Data Network (EMODnet), the primary gateway to European marine data, is the legal ambiguity surrounding U.S.-based cloud providers (Romanini et al., 2025).

Beyond regulatory challenges, the industry's reliance on digital interfaces introduces critical vulnerabilities related to the Human-Machine Interface (HMI). Recent behavioural studies, including eye-tracking research (Petrović and Vujičić, 2025), demonstrate that bridge officers are increasingly susceptible to *automation complacency* and cognitive tunnelling: a psychological state where an operator becomes so fixated on a single digital interface, that they ignore secondary instruments or the physical horizon. This human factor highlights that manual cross-referencing is no longer a guaranteed safeguard, creating an operational need for systems that automatically detect and flag data anomalies.

To mitigate these interconnected legal and operational risks, PETs offer a potential framework for secure processing (European Union Agency for Cybersecurity, 2018). Core technologies driving this transition include Homomorphic Encryption (HE), which allows computation on encrypted data, and pseudonymisation, which reduces identifiability in alignment with the GDPR. Collaborative environments benefit from Federated Learning (FL), enabling decentralised model training without centralising raw data, and Secure Multiparty Computation (SMPC), allowing parties to jointly compute results without disclosing inputs (Miller et al., 2025). These are often paired with blockchain-based authentication to ensure data integrity and automated compliance tools to support regulatory alignment across jurisdictions (Chintoh et al., 2025; Organisation for Economic Co-operation and Development, 2023).

Blue-Cloud 2026, a decentralized network designed to securely manage and share marine data, serves as a primary example of addressing data concerns through a federated approach aligned with FAIR principles (Findability, Accessibility, Interoperability and Reusability). This framework enables secure, cross-border access to marine data while avoiding the security risks associated with centralized, third-party storage. While Blue-Cloud provides a blueprint for federated sharing, it addresses only the network layer of a broader cyber-physical ecosystem. Consequently, simulation platforms like Cyber-MAR are essential to test holistic resilience and provide the hands-on training necessary to identify anomalies across the maritime supply chain (Romanini et al., 2025).

3. Methodology

This study employs a multi-method exploratory design to reconcile theoretical technical architectures with human operational realities across three interconnected pathways:

1. Legal-technical review: Evaluates the regulatory misalignment between horizontal privacy laws (GDPR) and maritime safety standards (IMO), cloud jurisdictional fragmentation, Human-Machine Interface (HMI) behavioral risks, and the structural capabilities of PETs.
2. Empirical survey: Conducted from 09/03/2026 to 06/05/2026 via a 22-question Google Forms instrument. Through purposive sampling, the survey targeted a dual-profile cohort: educators (professors, instructors and teachers) with seagoing experience currently active in Maritime Education and Training (MET). Participants were recruited via personal and institutional outreach to universities, academies, training centres and high schools. Data were processed using descriptive frequency analysis to evaluate perceived navigational vulnerabilities, the impact of cyber manipulation on situational awareness and current cybersecurity curriculum integration.

3. Design implications: Derives architectural recommendations for PET-enabled data verification frameworks based on the identified regulatory ambiguities and human cognitive gaps.

4. Survey Results

A total of 40 maritime professionals participated in the survey. The demographic breakdown of the cohort reflects the broader historical composition of the maritime sector: 92.5% of respondents were male ($n = 37$) and 7.5% were female ($n = 3$). The respondent pool represents a highly experienced demographic: 37.5% are Deck Masters, 25% are Chief Officers and 10% are Chief Engineers, alongside specialized roles such as Harbour Pilots. As academic instructors, the cohort is highly educated, with 42.5% holding PhDs and 30% holding Master's degrees. The results are analysed across operational dependencies, cyber vulnerabilities and educational frameworks.

4.1 Operational Dependence and Detection Latency

Data confirms a strong reliance on digital systems. In open-sea navigation, the vast majority of respondents (82.5%) report a large or very large reliance on ECDIS. Even during coastal navigation and port approaches, phases traditionally demanding rigorous cross-checking, digital reliance remains dominant. When examining coastal navigational tools, 60% report a large reliance on ECDIS and 70% rely heavily on Radar ranges and 72.5% on Radar overlays (see Figure 1).

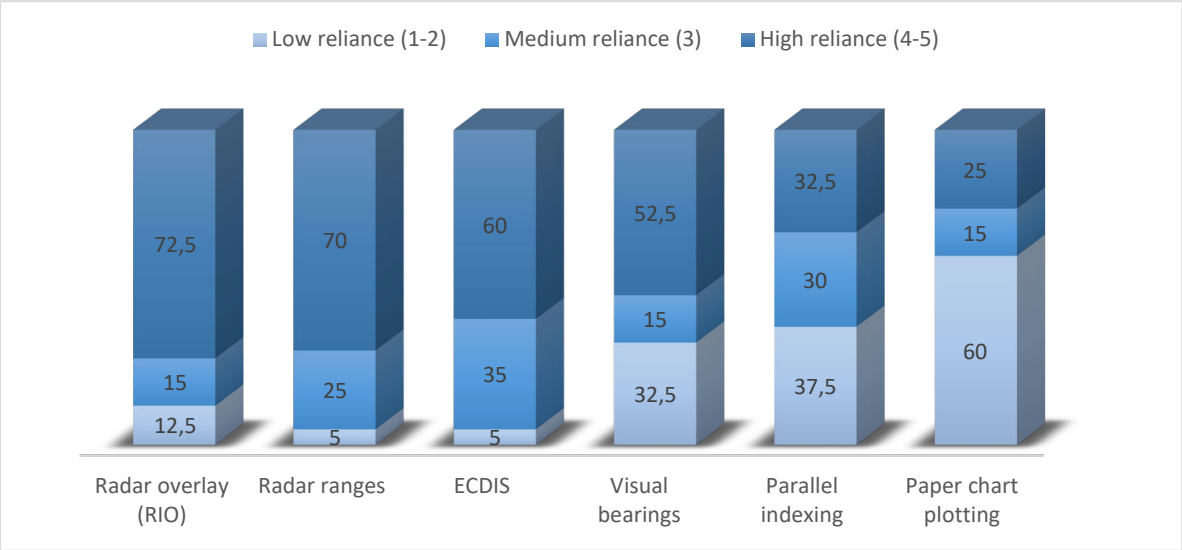


Figure 1. Navigational tool reliance in coastal waters.

Traditional manual cross-checking in restricted waters shows a marked decline. While the notably low usage of paper chart plotting (60% "never" or "rarely") largely reflects modern regulatory frameworks that permit *paperless* navigation via dual ECDIS setups, the concurrent decline in techniques like parallel indexing (37.5% "never" or "rarely") indicates a broader systemic shift. Bridge officers are heavily prioritizing integrated digital overlays over independent manual cross-checking.

A critical finding of this study is the geographical discrepancy in anomaly detection: coastal radar and landmarks enable immediate verification, whereas the open sea's *sensory vacuum* fosters digital reliance. As illustrated in Figure 2, when asked how quickly a crew would detect manipulation of GNSS or AIS data:

- Open sea: 87.5% of respondents believe detection would be critically delayed or missed. Specifically, 65% expect a "significant delay", 15% believe it "might not be detected" at all, and 7.5% state it would only be caught "if an external warning is received".

- Coastal waters: Conversely, 85% expect fast detection, either "within 15 minutes" (55%) or "immediately" (30%).

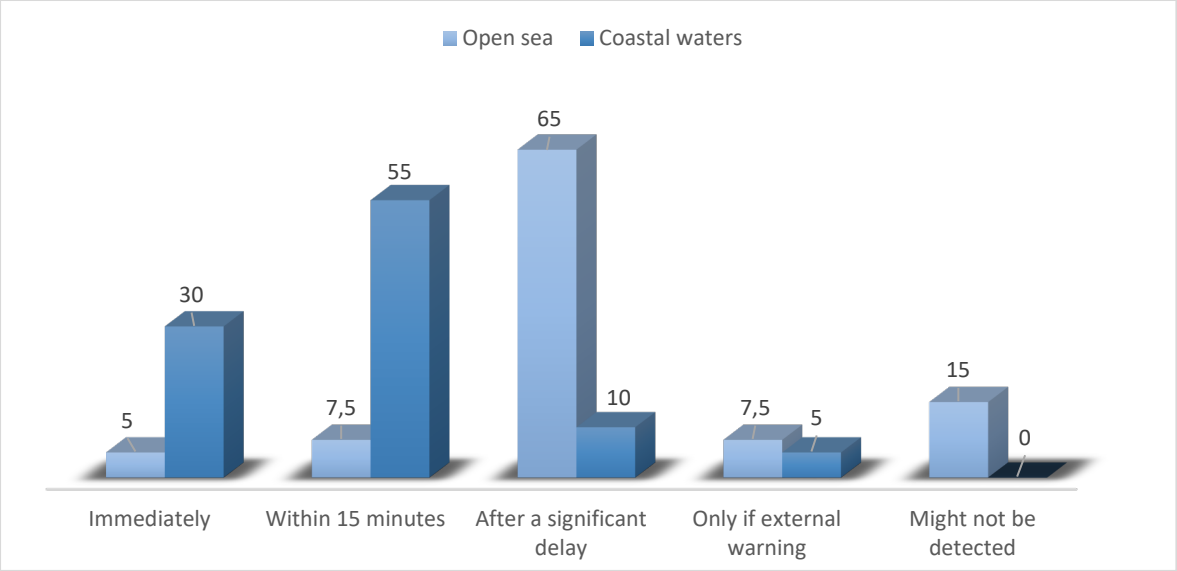


Figure 2. Anomaly detection speed by voyage phase.

This suggests a state of automation complacency during open-sea transit, where the lack of physical landmarks and reduced cross-referencing significantly increases the window of opportunity for a successful cyberattack.

4.2 Perceived Vulnerability and Situational Impact

Respondents show a sophisticated understanding of system architecture vulnerabilities. Systems reliant on external signals are viewed with the highest concern (refer to Figure 3): 75% rate GNSS as "highly" or "extremely" vulnerable, with AIS identically rated at 75%. Internal, self-contained systems are perceived as significantly more secure; specifically, the Gyrocompass (77.5% low vulnerability) and Speed log (80% low vulnerability) are viewed as the most resilient data sources in the navigational suite.

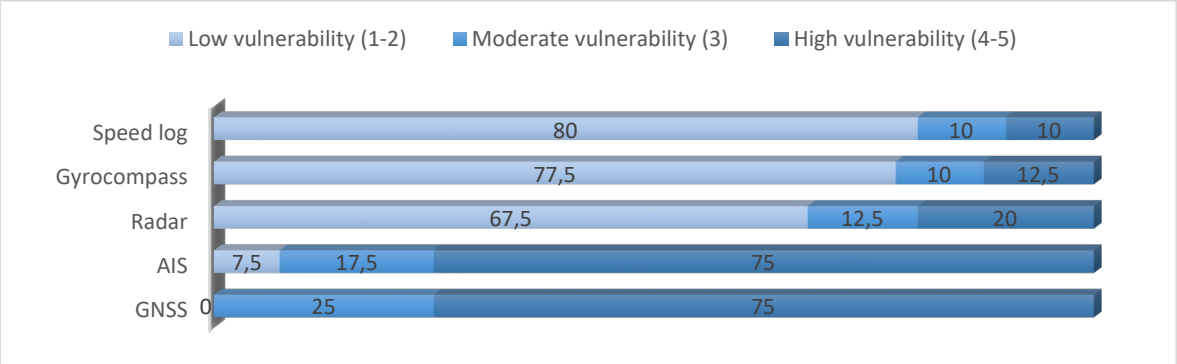


Figure 3. Perceived vulnerability of navigation systems.

Despite confidence in internal systems, the operational impact of an external breach is considered catastrophic. The majority of the cohort (72.5%) stated that manipulation of data inputs would result in a "severe degradation" or a "complete loss" of situational awareness.

4.3 Demographic Cross-Analysis: Experience vs. Risk Perception

A cross-tabulation of "Years of seagoing experience" against "Cyber risk perception" reveals a distinct generational divide in how officers evaluate the consequences of a cyber incident. While all experience levels

recognise the significant danger, younger officers (who are digitally native and have trained primarily on integrated bridges) perceive an even higher severity of degradation if systems fail.

As shown in Figure 4, 80% of Junior officers (those with 10 years of experience or less) believe that a manipulation of GNSS or AIS data would lead to a "severe degradation" or "complete loss" of situational awareness. This figure decreases among more experienced cohorts, with 70% of Seniors (11-20 years) and 60% of Veterans (over 20 years) sharing this view.

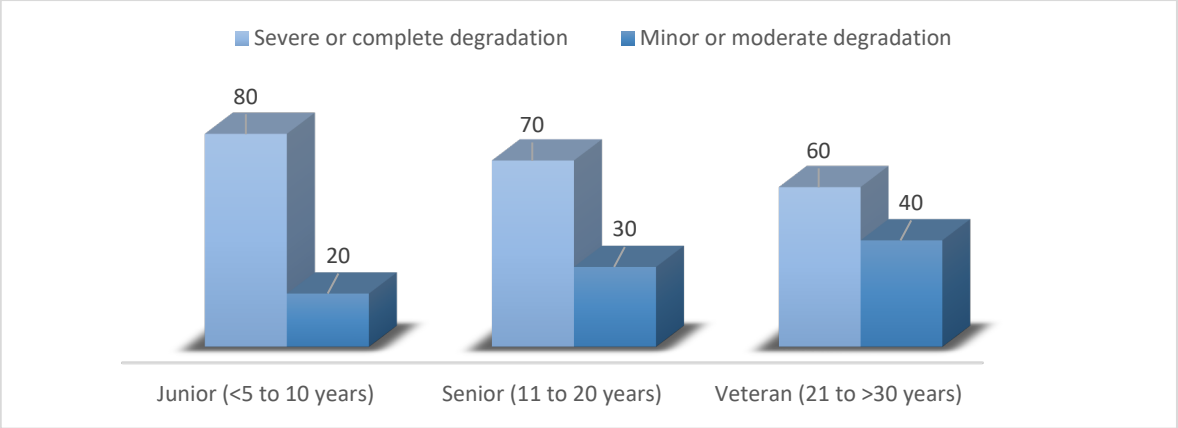


Figure 4. Risk perception of GNSS/AIS data manipulation by experience level.

This trend indicates that while veteran officers may rely more on their *maritime sense* and manual cross-checking abilities to mitigate data anomalies, the younger generation feels more fundamentally vulnerable to digital deception.

4.4 Governance, the "Education Gap" and Qualitative Recommendations

The data highlights a significant *trust gap* in maritime cloud environments (see Figure 5). Sharing vessel operational data with shore offices and third parties is viewed as a "high" or "very high" risk by half of the respondents (50%). Furthermore, confidence in Safety Management Systems (SMS) to protect this data is relatively low; only 32.5% of the cohort believes current procedures are adequate to a large or very large extent.

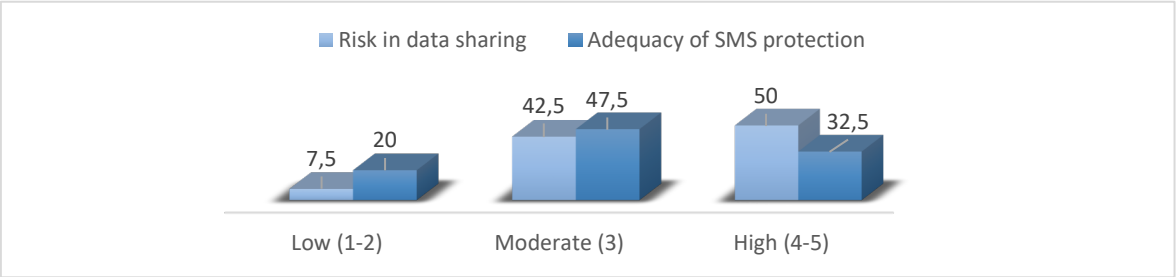


Figure 5. Perceived data sharing risk vs. SMS protection adequacy.

As detailed in Figure 6, the most alarming data point, especially given that the respondents are educators, relates to curriculum preparedness:

- Regulatory framework: 62.5% believe the current Standards of Training, Certification and Watchkeeping (STCW) Convention and the associated Certificate of Competency (CoC) framework are inadequate for preparing officers to manage modern cyber threats.
- Practical exposure: 57.5% of respondents state that students are "rarely" or "not exposed" to training scenarios involving cyber incidents.
- Curriculum inclusion: 57.5% report that cybersecurity is included to a "very small extent" or "not included" in their institutional programmes.

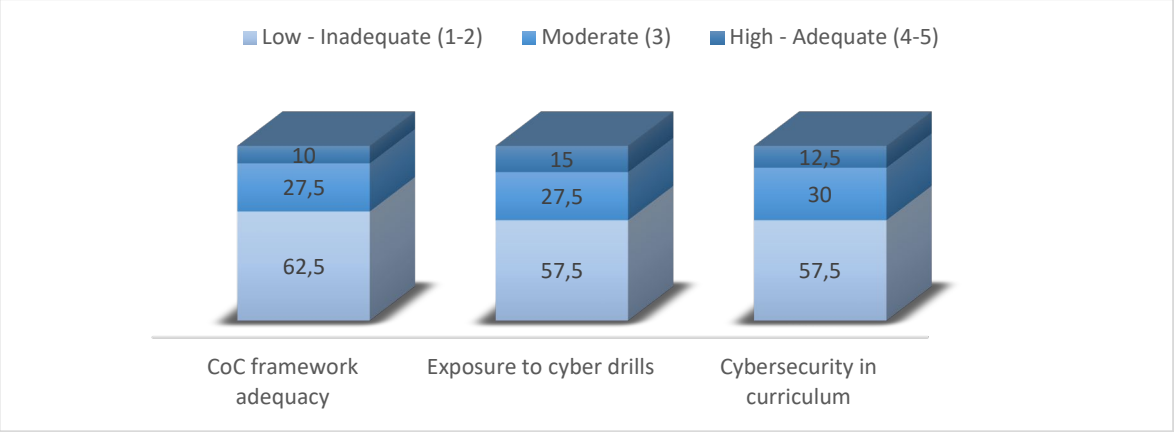


Figure 6. Adequacy of cybersecurity education and frameworks.

When asked in an open-text format to suggest measures to bridge this gap, respondents provided extensive commentary. A thematic analysis of these qualitative responses reveals four primary pillars for reform:

1. Simulation and drills: Educators strongly advocated for "*unannounced training exercises on the training bridge while underway*" and specific "*spoofing drills with visual stimuli*" to break automation complacency.
2. Real-world case studies: Several respondents emphasized the need to "*give and analyse more real life examples, such as the Maersk incident*", integrating these into existing Bridge Resource Management (BRM) training, rather than teaching abstract theory.
3. Train-the-Trainer: There was a consensus on the need to "*hire skilled professionals focused on maritime cybersecurity*" and to "*first, provide lecturers with training on cybersecurity topics*" to overcome the current competency gap among teaching staff.
4. STCW and critical thinking: Rather than treating cyber risk as an elective, participants stressed that training "*should be required by STCW*". One educator summarized the overarching human-element goal perfectly: "*We need to raise awareness among young people that IT isn't always the right answer. Therefore, we must always analyse the data*".

5. Discussion: Navigational Resilience and PET-enabled Verification

The empirical findings suggest that rapid digitalization has rendered the *human-in-the-loop* an insufficient fail-safe. Survey results demonstrate an overwhelming operational reliance on integrated displays: 60% of respondents report high reliance on ECDIS and 72.5% use Radar overlays for coastal verification, while 60% state that paper chart plotting is "never" or "rarely" used. This *paperless reality* means situational awareness is entirely digitally mediated, creating the psychological conditions for cognitive tunnelling, where officers become so focused on screen data that they ignore contradictory external cues (Androjna and Perkovič, 2021; Svilicic et al., 2020).

Behavioral insights from eye-tracking literature contextualize these risks. During simulated navigational cyberattacks, bridge officers consistently fixate on primary displays (ECDIS or Radar overlays) rather than scanning secondary instruments or the physical horizon (Petrović and Vujičić, 2025). This lack of visual scanning explains a stark detection discrepancy in the survey: while officers expect rapid anomaly detection in landmark-rich coastal waters, 87.5% admit that open-sea data manipulation would cause significant delays or a total failure to detect the incident. This is because in these unpiloted, open-water phases, the absence of external visual stimuli reinforces automation complacency, rendering the bridge team entirely dependent on the integrity of its data stream.

Since cognitive biases impede manual verification, PETs offer a data-driven technical safeguard more robust than mere regulatory compliance. Rather than expecting officers to detect a subtle 0.5-nautical-mile GNSS

spoofing drift, a task rendered nearly impossible by cognitive tunnelling, a PET-enabled architecture acts as a continuous digital auditor. By employing Secure Multiparty Computation to cross-reference GNSS signals against trusted internal sensors, such as the Gyrocompass and Speed log (which survey respondents identified as having low vulnerability: 77.5% and 80%, respectively), these systems validate positions without exposing sensitive raw data. This shifts the officer's role from passive observer to informed decision-maker, effectively breaking the cycle of automation complacency. Furthermore, since 57.5% of maritime educators report that cybersecurity is excluded or minimally included in their curricula, PETs provide a necessary operational bridge while the industry reforms its pedagogical standards.

6. Conclusion

The transition to paperless operations has structurally cemented digital reliance while removing traditional analog fallbacks. That 87.5% of professionals anticipate significant delays or total failure in detecting open-sea data manipulation highlights the need for PETs as a compensatory mechanism. Because the human element is highly prone to automation complacency, as corroborated by recent eye-tracking literature, manual checks are no longer a sufficient safety net on screen-dominated bridges.

Ultimately, maritime digitalization has vastly outpaced pedagogical adaptation. The proposed PET framework mitigates this friction through cognitive offloading. By automating multi-source data verification at the software layer, it acts as a *cryptographic prosthetic* that compensates for systemic training deficits, securing operations while long-term curricular reforms upskill the workforce.

Implementing these frameworks (particularly Federated Learning and Secure Multiparty Computation) provides the safeguards necessary to automate verification, offset cognitive limits and maintain supply chain predictability. Given the cascading global impacts of navigational paralysis at strategic chokepoints, technical solutions must align with broader policy frameworks, such as shared government-industry *go/no-go* criteria (Hashimoto, 2026). Yet, securing the maritime digital transformation extends beyond policy and software alone. Future socio-technical research must investigate how bridge teams interact with these automated tools under operational stress, ensuring they actively enhance human decision-making.

CRediT Author Statement

Daisy Romanini: Conceptualization, Investigation, Writing - Original Draft. **Marinella Petrocchi**: Conceptualization, Supervision, Writing - Review & Editing. **Fabio Pinelli**: Supervision, Writing - Review & Editing. **Fabio Martinelli**: Supervision, Writing - Review & Editing. **Srđan Vujičić**: Conceptualization, Supervision, Writing - Review & Editing

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Investigating human factor in ECDIS-related maritime accidents: insights from investigation reports and proposals towards safety improvements

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Abstract: The Electronic Chart Display and Information System (ECDIS) serves as the primary interface through which Officers of the Watch (OOWs) perceive, interpret, and manage the navigational environment. By structuring information and integrating multiple sensor inputs, the system supports voyage planning and monitoring, as well as hazard assessment throughout all phases of the voyage. Its contribution to safety, therefore, depends on how this mediated representation of the environment is understood, accepted, and used within the operational and organisational context of the navigational bridge. This study analyses maritime accidents involving ECDIS and uses the Human Factors Analysis and Classification System for Maritime Accidents (HFACS-MA). The results indicate that accidents are rarely associated with technical and/or system failure. Instead, they are predominantly linked to routine violations, inadequate supervision, and organisational climate, pointing to weaknesses within the human operating environment. To complement the findings, Port State Control (PSC) inspection data from the Australian Maritime Safety Authority (AMSA), and Tokyo and Paris Memorandums of Understanding were examined, revealing recurring deficiencies related to Electronic Navigational Charts (ENC) management, system configuration, alarm handling, and operator competence. Addressing these areas is essential for translating the technical capabilities of ECDIS into consistent and measurable safety outcomes in maritime navigation.

Keywords: safety of navigation; ECDIS; maritime accidents, human reliability analysis; human factor

1. Introduction

The rapid digitalization of maritime navigation has profoundly altered how navigational information is generated, displayed, and used on the navigational bridge. The ECDIS system has become a mandatory navigational means on board. By organizing information and integrating inputs from multiple sensors, the system enables effective voyage planning, monitoring, and assessment of navigational hazards across all stages of the maritime voyage. Its impact on safety depends on how this mediated representation of the environment is interpreted and applied within the operational and organizational context of the navigational bridge in terms of situational awareness, the use and management of safety settings, the adequacy of training, and system-related challenges (Hasanspahić et al., 2025). Discrepancies in system acceptance may lead to the intentional non-use of the system, potentially resulting in persistent and additional system-related issues (Car et al., 2020). Despite its widespread implementation and advanced technical capabilities, maritime accidents in which ECDIS usage plays a significant role continue to occur. Accident investigation reports repeatedly identify groundings and collisions in which ECDIS-related factors contribute to the development of unsafe navigational situations. Commonly reported issues include inappropriate safety settings, inadequate route planning, excessive reliance on automation, insufficient understanding of system functionality, and misinterpretation of displayed information (Turna and Öztürk, 2019). In many cases, ECDIS was available and operational, yet failed to prevent the accident. Mentioned indicates that navigational safety cannot be attributed solely to the presence of advanced systems, but rather to the complex interaction between humans, technology, and organisational context. From an operational perspective, ECDIS serves as the primary interface through which Officers of the Watch (OOWs) perceive, interpret, and manage the navigational environment. The system structures navigational information and represents the reality that supports hazard detection and decision making. Consequently, the contribution of ECDIS to safety depends on how this representation is understood, trusted,

and used by OOWs under varying operational conditions. Misalignment between system design, user expectations, training, and organisational procedures can significantly degrade navigational performance. These characteristics underscore the need for a human- and organisation-centred approach to ECDIS-related accidents.

The study aimed to analyse ECDIS-related maritime accidents in order to identify and classify key contributing causal factors, and to improve the understanding of their navigational safety role. Traditional accident analyses focus primarily on immediate operator errors or technical failures, often failing to capture deeper, systemic factors that shape navigational behaviour and operational environment. In this study, the Human Factor Analysis and Classification System – Maritime (HFACS-MA) framework was used, since it offers a structured method for examining accident causation across multiple levels with human factor assessment in critical maritime operations (Adumene et al., 2022; Chen et al., 2013). Applying the framework enabled the identification of latent conditions and systemic weaknesses that contribute to ECDIS-related groundings and collisions. By situating ECDIS use under the broader navigational bridge environment, we aimed to contribute to a more thorough understanding of how human and organisational factors influence navigational safety, and how they can be addressed. Integrating related accident analysis with the proposed framework provides a basis for identifying targeted interventions, ultimately supporting the prevention of future navigational accidents. Port State Control (PSC) inspection data provide an additional perspective on how ECDIS-related deficiencies manifest in operational practice. Inspection reports offer insight into the gap between formal compliance and actual performance on board ships.

2. Background

ECDIS was developed to enhance the safety and efficiency of maritime navigation by integrating electronic navigational charts with positioning, voyage, and environmental data. It is recognised under the International Maritime Organisation (IMO) framework and required by the International Convention for the Safety of Life at Sea (SOLAS) on most merchant vessels (IMO, 2020). It is used for route planning, route monitoring, safety checks, and the management of navigational information. Despite these capabilities, certain risks are associated with its use, including equipment-related (hardware or software failures, sensor errors, and power loss), chart-related (outdated or improperly updated ENC data or inability to access required charts), and operational risks related to system use. The impact of these risks depends on vessel type, operational conditions, and crew competence (Weintrit, 2011; Weintrit and Stawicki, 2008). ECDIS interfaces are not perceived in the same way by all users. They can be considered intuitive or, in some cases, complex and difficult to operate. This may lead to incorrect use or reduced situational awareness (Brčić et al., 2015). Previous studies have identified issues at different levels, including operational and organisational problems (Car et al., 2020). The HFACS-MA framework enables classification across hierarchical levels and distinguishes between unsafe acts, preconditions, supervision, organisational influences, and external factors (Chauvin et al., 2013). It includes maritime-specific modifications and additional elements relevant for accident analysis (Chen et al., 2013). Previous studies have also analysed ECDIS-related issues in accidents. In grounding cases, problems related to system configuration, alarm settings, and training have been identified as contributing factors (Turna and Öztürk, 2019). Although ECDIS improves the safety of navigation, its effectiveness depends on its practical usage on board.

3. Methodology

The study adopted a methodological approach combining qualitative accident investigation analysis using the HFACS-MA framework (Figure 1) with a quantitative, independent review of Port State Control (PSC) detention data. The aim was to identify and classify all factors associated with ECDIS-related accidents and to compare them with operational, recurring deficiencies observed in detentions. The analysed detentions were not linked to the accidents presented in Table 1, but were used to identify recurring ECDIS-related deficiencies detected during PSC inspections. The framework represents a top-down influence structure in which external factors, organisational influences, and supervision shape the conditions under which operators interact with ECDIS and perform navigational tasks. In parallel, a bottom-up monitoring flow captures how information from operational levels, including system use and observed deficiencies, propagates upward and should inform supervision, organisational control, and regulatory oversight.

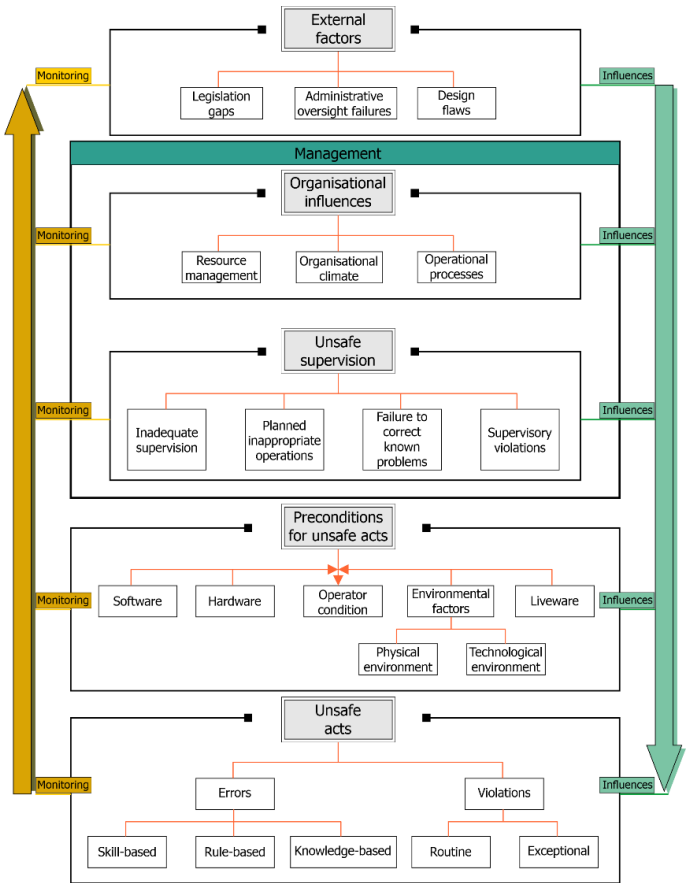


Figure 1. HFACS-MA method. Adopted from (Chen et al., 2013)

Maritime accident investigation final reports were collected from official sources (MAIB, 2025; DMAIB, 2025; MSIU, 2025; BSU, 2025; BEAmer, 2025; NTSB, 2025; TAIC, 2025). Reports were included based on explicit or clearly inferred involvement of ECDIS/ECS (Electronic Chart System) in the accident sequence, sufficient detail to identify causal and contributory factors, and relevance to navigational decision-making or bridge operations. Other cases were excluded. The unit of analysis was defined as a causal statement, understood as any explicit or implicit description within the report that links an action, condition, or decision to the development of the accident. Statements were extracted from analysis sections, conclusions, and identified contributory factors. Each statement was treated as an individual analytical unit and prepared for classification. A directed qualitative content analysis was conducted using the HFACS-MA framework as a predefined classification structure (Chen et al., 2013; Chauvin et al., 2013). The coding procedure consisted of the following steps.

During initial identification of contributing factors, extracted causal statements were reviewed and interpreted in their full context. Each statement was assigned to one or more categories within the five HFACS-MA levels: *i)* external factors, *ii)* organisational influences, *iii)* unsafe supervision, *iv)* preconditions for unsafe acts, and *v)* unsafe acts. The assignment was based on the primary contributing factor described in the statement and its role in the accident sequence. Multiple coding was allowed where a factor reflected interactions across levels. Special attention was given to factors directly related to ECDIS configuration and settings, interpretation of displayed information, route planning and monitoring using ECDIS, and interaction between operator and system. Causal factor coding was done jointly by the authors of the study (academicians and maritime professionals) based on a consensus decision. If there were some ambiguities, they were solved through discussion. Coding process prioritised causal relevance over descriptive detail. It is acknowledged that accident reports reflect the perspective of investigating authorities and may contain inherent biases. However, the aim of the study was not to re-analyse the accidents but to classify causal factors and identify the most prominent ones.

To complement accident-based findings, PSC detentions were analysed using reports from AMSA (2025), Tokyo MoU (2025), and Paris MoU (2025), with the focus on frequency of detentions, occurrence and type of ECDIS- and PNC-related deficiencies and PSC Concentrated Inspection Campaigns (CIC) related to ECDIS.

4. Results

From 2008 to 2022, a total of 32 accidents occurred involving vessels equipped with ECDIS or ECS as the primary or secondary navigation system, being direct or indirect cause (Table 1).

Table 1. Maritime accidents involving ECDIS or ECS as a primary or secondary means of navigation.

Accident No.	Date	Vessel name	Type of accident	Equipment
1.	25. 10. 2021.	Chem Alya	Grounding	ECDIS
2.	7. 1. 2021.	Ocean Princess	Collision	ECDIS
3.	28. 3. 2020.	Key Bora	Grounding	ECDIS
4.	23. 3. 2020.	Kaami	Grounding	ECDIS
5.	8. 5. 2019.	Seatruck Performance	Grounding	PNC
6.	19. 4. 2019.	APL Danube	Grounding	ECDIS
7.	21. 10. 2018.	Red Falcon	Grounding/Collision	PNC
8.	18. 7. 2018.	Priscilla	Grounding	ECDIS
9.	9. 7. 2018.	Pazifik	Grounding	ECDIS
10.	27. 3. 2018.	Celtica Hav	Grounding	PNC
11.	12. 7. 2017.	Kea Trader	Grounding	ECDIS
12.	28. 6. 2017.	Freya	Grounding	ECDIS
13.	13. 5. 2017.	Universal Durban	Grounding	ECDIS
14.	6. 4. 2017.	MV Umm Salal	Grounding	ECDIS
15.	9. 2. 2017.	L'Austral	Grounding	ECDIS
16.	3. 12. 2016.	Muros	Grounding	ECDIS
17.	22. 8. 2016.	CMA CGM Vasco de Gama	Grounding	ECDIS
18.	11. 5. 2015.	Hamburg	Grounding	PNC
19.	18. 2. 2015.	Lysblink Seaways	Grounding	PNC
20.	14. 7. 2014.	Commodore Clipper	Grounding	ECDIS
21.	11. 1. 2014.	Rickmers Dubai	Collision	ECDIS
22.	18. 9. 2013.	Ovit	Grounding	ECDIS
23.	1. 8. 2013.	DART	Grounding	ECDIS
24.	12. 12. 2012.	Beaumont	Grounding	PNC
25.	9. 8. 2011.	CSL Thames	Grounding	ECDIS
26.	30. 4. 2010.	Beluga Revolution	Grounding	PNC
27.	10. 2. 2010.	Sichem Osprey	Grounding	PNC
28.	16. 9. 2009.	Maersk Kendal	Grounding	PNC
29.	29. 6. 2008.	Antari	Grounding	PNC
30.	12. 5. 2008.	CFL Performer	Grounding	ECDIS
31.	31. 1. 2008.	Pride of Canterbury	Grounding	PNC
32.	2. 1. 2008.	LT Cortesia	Grounding	PNC

Source: Made by authors based on (MAIB 2025; DMAIB 2025; MSIU 2025; BSU 2025; BEAmer 2025; NTSB 2025; TAIC 2025)

PNC denotes Paper Navigational Charts. In these cases, ECDIS or ECS was available on board but was not used as the primary means of navigation. Accidents 1–9 occurred after the completion of the ECDIS transitional period; those numbered 10–24 occurred during the transitional period; while accidents 25–32 occurred before the transitional period, although the systems were already in use.

Causal factors indicate that the biggest share of individual factors falls under the group of routine violations (9.9 %), followed by inadequate supervision (8.4 %) and organizational climate with planned inappropriate operation, each of which took 7.9 % of the total share (Table 2). The share of an individual category in the total number of accidents is as follows: preconditions level has the biggest share (29 %), followed by unsafe acts

(26 %), unsafe supervision (24 %), and organisational influences (14 %). The smallest share (7 %) falls under the category of external factors.

Table 1. Causal factors of analysed accidents within the HCASC-MA framework.

Causal factors levels	Causal factor categories	Share of frequency (%)
External Factors	Legislation gaps	2.1
	Administrative oversights	3.1
	Design flaws	2.1
Organisational Influences	Resource management	3.1
	Organisational climate	7.9
	Organisational process	2.6
Unsafe Supervision	Inadequate supervision	8.4
	Planned inappropriate operations	7.9
	Failure to correct known problem	3.1
	Supervisory violations	5.2
Preconditions	Operator condition	6.8
	Software	4.7
	Hardware	5.2
	Physical environment	5.8
	Technological environment	4.7
	Liveware	1.6
Unsafe Acts	Skill-based errors	3.7
	Rule-based mistakes	3.1
	Knowledge-based mistakes	2.6
	Routine violations	9.9
	Exceptional violations	6.3

Source: Made by authors based on (Chen et al. 2013)

Regarding categories, the most common ones identified were Routine violations (9.9%), Inadequate supervision (8.4%), followed by Planned inappropriate operations (7.9%) and Organisational climate (7.9%).

Inspections show the presence of ECDIS- and PNC-related deficiencies across all inspection regimes, rarely acting as the sole cause of detention (AMSA, 2025; Tokyo MoU, 2025 and Paris MoU, 2025) (Figure 2).

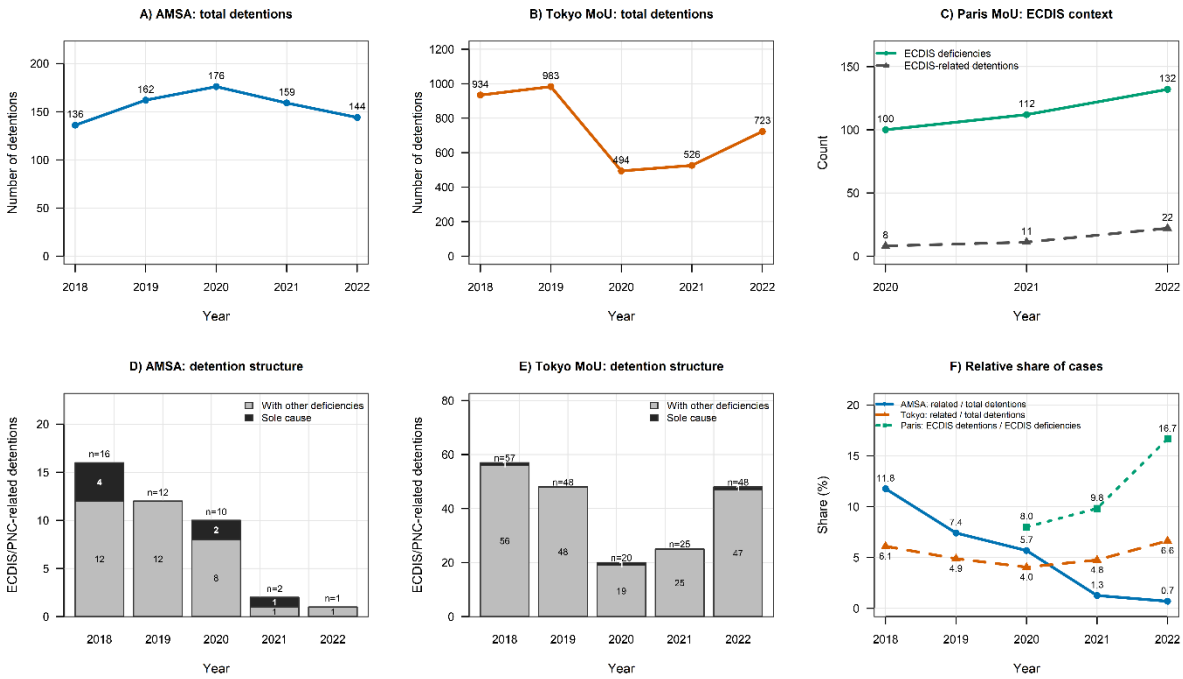


Figure 2. Port State Control patterns related to ECDIS and paper chart deficiencies: (A) AMSA total detentions, (B) Tokyo MoU total detentions, (C) Paris MoU ECDIS deficiencies and ECDIS-related detentions, (D) AMSA ECDIS/PNC-related detention structure, (E) Tokyo MoU ECDIS/PNC-related detention structure, and (F) relative share of ECDIS-related cases.

In the period 2018 – 2022, under AMSA inspections, a total of 777 ships were detained. Related deficiencies were identified on 41 ships, while only 7 detentions were attributed exclusively to these. A decreasing trend in such deficiencies is observed over time (AMSA 2025). Under the Tokyo MoU, 3,660 ships were detained. ECDIS- and PNC-related deficiencies were recorded on 198 ships, while only 3 detentions were caused solely by these deficiencies. A temporary reduction in total detentions is visible in 2020 to 2021, followed by a recovery in 2022 (Tokyo MoU, 2025). Paris MoU data (2020 to 2022) show a different pattern; detentions directly linked to ECDIS-related deficiencies increased from 8 cases in 2020, to 11 in 2021, and 22 in 2022, indicating a recent upward trend (Paris MoU, 2025). Across all datasets, the same patterns are consistently identified. The highest number of non-compliances is related to voyage planning, particularly cases where the plan is not prepared for the entire voyage, corresponding to Organisational climate, Inadequate supervision, and Routine violations as per HFACS-MA categories. A second group of frequent deficiencies relates to ENC management, including missing or outdated charts and inadequate backup arrangements, corresponding to Resource management, Hardware, and Rule-based mistakes. At the same time, deficiencies related to formal compliance are significantly less pronounced. PSC CIC data show low levels of non-compliance in areas such as STCW certification (around 0.5%), while the highest number of negative findings refers to voyage planning deficiencies (e.g., 338 negative responses) (Tokyo MoU, 2018), as identified by the reviewed inspections results dataset.

Overall, the results indicate that ECDIS-related deficiencies are not isolated technical failures, but are consistently associated with the execution of navigational tasks (ClassNK, 2016; Paris MoU, 2017 and Tokyo MoU, 2018).

5. Discussion

Navigation safety outcomes stem from the interaction among human operators, technological systems, and the operational environment. In complex navigational settings, inappropriate configuration or selective use of system functions can distort the representation of environmental risk, directly impacting OOW's situational awareness. At the voyage level, inconsistencies in training, supervision, and procedural control weaken the role of ECDIS as a reliable, primary navigational means. Further safety improvements will depend on treating ECDIS as a socio-technical control system rather than a standalone technical aid. Priority actions include focusing training on operational use and configuration practices, strengthening simulator-based system assessment, integrating it more explicitly into bridge resource management, and aligning organisational procedures with actual practice. The safety contribution of ECDIS cannot be evaluated solely through its technical capabilities. In spite of its benefits, the analysis demonstrated that accidents are rarely the result of isolated operational mistakes. Instead, they emerge from systemic interactions across organisational, supervisory, and operational levels, forming an unwanted chain of errors. This supports a socio-technical understanding of maritime safety in which technology, human performance, and organisational structures are tightly interdependent. ECDIS mediates the OOW's perception of the environment. When properly configured and competently used, it enhances hazard detection and decision-making. However, excessive trust in automated representations, insufficient cross-checking with independent sources, or incomplete understanding of system functionalities can, and will, degrade performance. At the organisational level, aligning procedures, supervision, and safety culture with the operational realities of digital navigation is essential to prevent mismatches between formal requirements and practical navigational bridge operations. Categories like routine violations usually occur naturally and are often tolerated by management. They occur during the performance of a particular procedure because humans regularly change or do not strictly follow work procedures, often because they are poorly designed, inadequately defined, or too complex (Chen et al. 2013). Some of the identified routine violations act as serious threats to the safety of navigation. In certain cases (MAIB 2025), when taking over the navigational watch, the OOW did not check the ship's planned route for navigational hazards that might arise during his watch. In one accident case, the absence of a lookout during the night watch prevented timely detection of an OOW who had fallen asleep. Finally, in order to reduce OOW workload, in some cases, the routinely automated functions were disabled. Inadequate supervision category includes situations where a superior officer or the master fails to identify a hazard, recognize and control a risk, provide instructions, training or supervision, which leads to an error or unsafe situation (Chen et al. 2013). In other cases, the master did not check and approve the changed route, the passage plan was not properly checked, the master

failed to exercise his superior authority for the ship's safety in order to delay departure from port while his OOWs were not adequately rested (MAIB 2025).

When looking at the PSC results, they point to a clear pattern. The problem is not the absence of regulations, equipment, or certification, but their practical application. Ships meet formal requirements, and OOWs hold valid certificates, yet deficiencies appear in tasks that require actual system use. The concentration of deficiencies in voyage planning and ENC management is critical. These elements directly shape how the navigational situation is constructed. Errors at this level influence the entire decision-making process, rather than representing isolated operational deviations. The contrast between high compliance in certification and frequent deficiencies in operational tasks confirms that training does not fully translate into practice. This suggests that current training approaches are focused on compliance and basic system use, but insufficiently address real operational conditions, including system configuration and decision-making under constraints. The fact that ECDIS-related deficiencies rarely appear as the sole cause of detention (e.g., 7/777 (AMSA 2025); 3/3660 (Tokyo MoU 2025)) further supports this interpretation. These deficiencies are embedded within a broader set of organisational and operational issues.

Inspection-related findings are consistent with the accident analysis results, where technical failures are not dominant. Instead, unsafe acts, supervision issues, and organisational influences shape how ECDIS is used. It should therefore be understood as part of a complex operational environment, not as a standalone technical solution. From a safety perspective, further improvements should focus on strengthening training in operational use and configuration, increasing the role of simulator-based assessment, and aligning procedures with actual working conditions on board.

The study is based on investigation reports issued by different authorities (MAIB, 2025; DMAIB, 2025; MSIU, 2025; BSU, 2025; BEAmer, 2025; NTSB, 2025; TAIC, 2025), whose methodological approaches and emphasis on human, technical, organisational, or regulatory factors may differ. Such differences may have influenced the identification and distribution of HFACS-MA categories. Nevertheless, the inclusion of reports from multiple authorities provides a broader perspective on ECDIS-related accidents and reduces dependence on any single investigative approach. The classification of contributing factors within the HFACS-MA structure, although systematic, involves interpretative judgment and may be influenced by reporting biases. As the analysis is based on accident cases, the identified factors reflect conditions associated with navigational failure involving ECDIS. They should not be interpreted as a general assessment of ECDIS use, since comparable non-accident cases were not included. Bearing these limitations in mind, future research should expand data and include direct observational studies for further validation. This study contributes to the different systemic approaches to maritime accident analysis; by combining structured human factors analysis with regulatory inspection data, it offers a layered perspective on navigational risks. The results suggest that improving maritime safety requires coordinated interventions across technological design, crew training, organisational governance, and regulatory oversight. Ultimately, the effectiveness of ECDIS as a safety tool depends not only on its technical reliability but on the broader socio-technical system in which it is embedded.

6. Conclusions

This paper analysed ECDIS-related maritime accidents using the HFACS-MA framework and complemented the results with PSC inspection data. The system is rarely the direct and sole cause of accidents. Instead, problems arise from how the system is used in practice. The analyses indicated that unsafe acts on the bridge are not isolated events. They are rather linked to organisational weaknesses, inadequate supervision, and conditions that shape OOW's performance, as well as the environment. Inspections' analyses support these statements. Deficiencies are most often related to voyage planning, ENC management, and system use, while compliance with formal requirements is generally not an issue. This points to a clear gap between formal compliance and actual operational performance. ECDIS is available, officers are certified, and procedures exist, however they are not consistently applied in real conditions. Improving safety, therefore, does not depend on introducing new requirements, but on improving how existing systems and procedures are used. Sustainable safety improvement requires an alignment of human performance, system configuration, and organisational control with actual operational conditions on board.

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From Radar to Artificial Intelligence: Mapping Contemporary Technologies for Marine Oil Spill Detection

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Abstract: Oil spills continue to pose a persistent and globally significant threat to the marine environment, causing long-term ecological and economic impacts and necessitating timely and reliable detection for effective response. Consequently, the development of advanced technologies for the detection and analysis of oil spills is a crucial research and operational issue. This paper aims to develop and apply an integrated methodological framework for identifying, grouping, and evaluating modern technologies for marine oil spill detection, combining bibliometric analysis and multi-criteria decision-making. A literature review and bibliometric analysis of contemporary technologies for marine oil spill detection were conducted. Six main technology clusters were defined based on the identified technologies. The AHP/TOPSIS multi-criteria decision-making method was used to rank the technologies according to eight criteria. The results indicate that the combination of SAR/PolSAR satellite systems and AI-driven data fusion approaches achieves the highest overall performance and represents the most promising direction for developing future systems for early detection and response to oil spills in the marine environment. These results also highlight a shift towards integrated decision-support systems based on satellite and AI technologies. Overall, such an approach can play an important role in detecting oil spills and consequently reducing their environmental impact.

Keywords: bibliometric analysis; marine environment; oil spill detection; contemporary technologies; AHP/TOPSIS

1. Introduction

Despite significant progress in international regulations and safety standards, maritime transport and its infrastructure still pose risks of accidental and intentional spills, leading to significant environmental and economic consequences. Accidents involving oil cause damage to marine ecosystems, biodiversity, and human health (Keramea, Zodiatis and Sylaios, 2026). Oil spill monitoring is crucial for responding to marine oil pollution, as it provides the information needed for effective response actions (Xie *et al.*, 2025). Furthermore, to act quickly and reduce marine pollution, and consequently protect the marine environment, timely and effective oil spill detection is necessary (Lau and Huang, 2024). Over the past decades, there has been a significant technological shift towards the application of remote sensing, which enables rapid and spatially extensive monitoring of sea surfaces (Fingas and Brown, 2017; Xie *et al.*, 2025).

A wide range of technologies for oil spill detection have been developed, including radar and satellite systems (especially SAR technology), optical and thermal infrared sensors, spectroscopic methods, and other remote sensing approaches (Brekke and Solberg, 2005; Topouzelis, 2008; Angelliaume *et al.*, 2018; Ouchi and Yoshida, 2023). Modern approaches increasingly include artificial intelligence, machine learning and multi-sensor data fusion, as well as autonomous platforms, which significantly improves detection accuracy and operational applicability of systems (Yekeen and Balogun, 2020; Zhu *et al.*, 2022; Liu *et al.*, 2023). In addition, the development of integrated systems for visualization, modeling and early detection enables advanced analysis and prediction of the spread of pollution. Despite significant progress, most of the existing research is still focused on individual technologies or specific applications, without a systematic and quantitative comparison of their performance. Furthermore, modern approaches increasingly involve the integration of multiple technologies, which erases the boundaries between individual methods and emphasizes the need for evaluation at the level of complex technological systems.

In this context, multi-criteria decision making methods provide a suitable framework for analyzing and ranking different technological approaches based on multiple criteria (Saaty, 1987). Particularly noteworthy is the combination of the Analytical Hierarchical Process (AHP) and the TOPSIS method, which makes it possible to determine the relative importance of criteria and rank alternatives according to their proximity to the ideal solution (Ogonowski, 2022).

The aim of this paper is to develop an integrated methodological framework that combines a systematic literature review, bibliometric analysis and AHP–TOPSIS multi-criteria ranking in order to enable objective evaluation and ranking of technology clusters in the field of marine oil pollution detection.

The main contribution of the paper is reflected in the transition from the analysis of individual technologies to the evaluation of technology clusters, which enables a more realistic assessment of modern, interdisciplinary and hybrid detection systems. The proposed approach enables the identification of dominant and promising technological directions and provides insight into development trends that indicate the increasing role of integrated, automated and AI-assisted systems in future marine environment surveillance operations.

2. Materials and Methods

This paper develops an integrated methodological framework that combines literature search, bibliometric analysis, technological grouping and Analytic Hierarchy Process (AHP)/TOPSIS multi-criteria ranking of modern technologies for detecting of marine oil pollution. The methodological framework of five steps is further described and presented in Figure 1.

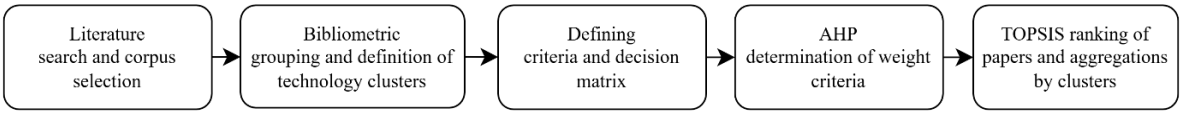


Figure 1. Research methodological framework.

2.1 Literature Search and Corpus Selection

The methodological process began with literature search in the Web of Science (WoS) database (Clarivate, 2025)**,** conducted on 15 May 2025 using the query: "new technologies AND oil spill AND (ocean OR sea OR marine)" in Topic. The initial search identified 210 publications**.** After that, a two-stage filtration process was carried out. In the first step, bibliographic metadata, including the year of publication, the title of the paper, the source of the publication, and the number of citations, were reviewed to remove papers that were clearly unrelated to the topic. In the second step, the abstracts of the papers were systematically analysed in order to confirm that the research is directly related to the development, application or evaluation of modern technologies for the prevention, detection, monitoring or response to marine oil pollution**.** After the filtering process, 63 papers were retained**,** which form the final corpus for bibliometric analysis, construction of technological clusters and further multi-criteria ranking.

2.2 Bibliometric grouping and definition of technology clusters

The methodology begins with a bibliometric analysis of keyword co-occurrence and the functional similarity of technologies within the analysed corpus of papers. VOSviewer's keyword analysis (van Eck and Waltman, 2009) initially identified five topic clusters. However, these clusters did not always correspond to a single technology, as they often included sensors, AI methods, and operational platforms together. Consequently, they were consolidated into six final technology clusters, each representing clearly comparable technological approaches for further AHP–TOPSIS analysis. Table 1 provides a brief description of the final technology clusters, including their content, main advantages, and limitations, forming the basis for constructing the decision matrix.

Table 1. Final technology clusters derived from the reviewed literature

Cluster code	Technology cluster	Included technologies	Key operational advantages	Main operational limitations
C1	Conventional SAR / PolSAR	SAR, PolSAR, Sentinel-1, SAR+AIS	day/night operation, all-weather capability, wide-area coverage	look-alike phenomena, dependence on platform revisit time, downlink, and product availability
C2	Optical / hyperspectral / multispectral	multispectral, hyperspectral, AVIRIS, UAV optical	very high spectral discrimination, oil thickness estimation, emulsion characterization	cloud cover, sun glint, daylight dependency
C3	Thermal infrared / IR polarimetry	LWIR, SWIR, IR polarimetry	night-time operation, thermal contrast, rapid local boundary mapping	dependence on temperature conditions and time of day
C4	UAV / ASV / AUV robotic platforms	UAV, ASV, AUV, gliders, multi-agent systems	rapid deployment, local flexibility, direct response capability	limited spatial coverage, weather sensitivity
C5	LIF / fluorescence / spectroscopy	LIF, fluorometers, spectroscopy, GC/MS	rapid oil type identification, forensic support, high chemical specificity	very limited spatial coverage, mainly local application
C6	AI / deep learning / data fusion	CNN, ViT, multimodal fusion, AIS+SAR+meteo	automation, faster and improved classification, decision support, multisource fusion	dependence on input data quality and model training

To enable multi-criteria ranking of technological approaches, each analysed paper from the final set of literature was assigned one primary technology cluster and, if necessary, one or more secondary clusters, based on the dominant technologies identified through keywords, title, and abstract.

2.3 Defining criteria and decision matrix

Eight criteria have been defined for the AHP–TOPSIS analysis, based on three interrelated bases. The criteria were selected to capture technological performance, operational applicability, technological maturity, and emergency response requirements that repeatedly emerged across the analysed literature. The first basis comprises dominant technological performance, identified through the analysis of abstracts, keywords, and methodological approaches in selected papers, with detection accuracy, resistance to weather conditions, speed of obtaining results, spatial coverage, and level of automation being the most common. The second basis concerns the operational requirements of actual early warning and emergency response systems in the maritime environment, including applicability in coast guard operations, port incidents, offshore surveillance, and sudden spill response systems. The third basis consists of bibliometric indicators of the maturity and renewability of the technology, derived from the number of citations and the year of publication of the analysed papers, to include the developmental stability and topicality of a particular technological approach in the evaluation.

Table 2. Multi-criteria evaluation criteria

Criterion	Description
Acc = Accuracy	Reliability of distinguishing oil spills from other phenomena on the sea surface.
Wea = Weather robustness	Ability to operate reliably in a variety of weather and sea conditions.
Tim = Timeliness	The speed of generating operationally useful information after data acquisition.
Cov = Spatial coverage	The spatial extent that technology can effectively monitor.
Auto = Automation potential	Possibility of integration into automated workflows, AI processing and alert systems.
Emerg = Emergency response suitability	Suitability of the technology for emergency spill response scenarios.
Mat = Maturity	The level of technological and bibliometric maturity of the approach.
Rec = Recency	Current technology according to the year of publication and recent literature.

Maturity was derived from the number of citations of the analysed papers. Since older papers naturally accumulate a larger number of citations, this criterion is not interpreted in isolation, but together with the

Recency criterion, which introduces the temporal dimension of the actuality of the technology. They were normalized to a scale of 1–5, in order to be comparable with other criteria according to the following relationships:

$$Mi = 1 + 4 \cdot \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (1)$$

$$Ri = 1 + 4 \cdot \frac{y_i - y_{min}}{y_{max} - y_{min}} \quad (2)$$

where x_i is number of citations of the paper *i*, x_{min} i x_{max} minimum and maximum number of citations in the analysed corpus, while y_i denotates the year of publication of the paper *i*, a $y_{min\_}$ i y_{max} the earliest and most recent year of publication in the set of papers.

2.4 Final cluster evaluation matrix

As the TOPSIS method requires a numerical decision matrix, the qualitative characteristics of the final technology clusters from Table 1 were converted into ordinal scores on a scale of 1–5, where 1 represents very low and 5 very high suitability for each criterion. The assessments were conducted by the authors based on the dominant technical characteristics of the sensors and platforms, the recurring advantages and limitations identified in the analysed literature, and operational applicability in real oil spill scenarios.

For example, cluster C1 (Conventional SAR / PolSAR) received the highest marks for Weather robustness (value=5) and Coverage (value=5) due to its ability to operate in all weather conditions, day and night, and it's very high satellite coverage. However, the Timeliness criterion was rated 3, as the timeliness of operational information is limited by the satellite's revisit time, downlink process, data processing, and the moment when the operator actually receives the image.

Special attention was given to the Automation potential criterion, which assesses the possibility of integrating a particular technology into automated workflows, AI classification, onboard data processing, alert systems, and decision-support environments. Therefore, the C6 (AI/deep learning/data fusion) cluster received a maximum score of 5, as it represents technologies based on automated classification, multimodal data fusion, and intelligent decision support. Similarly, the C4 (UAV/ASV/AUV robotic platforms) cluster is also highly rated (value=5) for its autonomous navigation capabilities, automatic spill monitoring, and direct integration into response systems.

On the other hand, cluster C5 (LIF/fluorescence/spectroscopy) received the highest score for Accuracy (value=5) because of its very high chemical specificity and its ability to identify the type of oil, but a low score for Coverage (value=1) due to the local and point nature of the measurement.

Thus, the final cluster evaluation matrix (Table 3) was created, representing the input decision matrix for further AHP–TOPSIS multi-criteria analysis and ranking of technological approaches to oil spill detection in the marine environment.

Table 3. Final cluster evaluation matrix

Cluster code	Technology cluster	Accuracy	Weather	Timeliness	Coverage	Automation	Emergency
C1	Conventional SAR/ PolSAR	4	5	3	5	3	5
C2	Optical/hyperspectral/ multispectral	5	2	3	4	4	4
C3	Thermal infrared/IR polarimetry	4	3	4	3	4	4
C4	UAV/ASV/AUV robotic platforms	4	2	5	2	5	5
C5	LIF/fluorescence /spectroscopy	5	4	4	1	4	5
C6	AI/deep learning /data fusion	5	4	5	4	5	5

2.5 Determination of the weights of criteria using the AHP method

The relative importance of the eight criteria was determined by the AHP method based on paired comparisons according to the scale 1–5, where 1 indicates equal importance and 5 indicates strong importance. The pairwise comparison matrix was constructed based on the authors' evaluation, informed by bibliometric analysis, technological interpretation of the literature, and domain knowledge in the field of maritime surveillance. An analysis of the Consistency Index CI (3) and the Consistency Ratio CR (4) were performed on the basis of the results of bibliometric analysis, technological interpretation of literature and domain knowledge in the field of maritime surveillance. According to Saaty, the pairwise comparison matrix is considered acceptably consistent when CR≤0.10; otherwise, the judgments should be revised.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

$$CR = \frac{CI}{RI} \tag{4}$$

where n is the number of criterions, λ_{max} is the maximum eigenvalue of the pairwise comparison matrix, and RI is Saaty's random consistency index corresponding to the matrix size (Ogonowski, 2022) .

2.5 TOPSIS method for ranking papers

In the final phase of the methodology, the TOPSIS method was used to rank the analysed papers from the literature corpus. Each paper is linked to one primary technology cluster and to one or more secondary clusters when the work incorporates multiple technologies. The criterion values for each paper were calculated as a weighted average of the grades of the relevant clusters, with the primary cluster assigned a weighting of 50%, and the remaining 50% evenly distributed among the secondary clusters. This approach enables hybrid papers to maintain their multimodal technological nature, while preserving the dominant methodological component through the primary cluster.

By ranking papers in this manner, the numerical priority of each technological approach within the bibliometric corpus is established. As each paper contains information about its association with one or more technology clusters, aggregating the TOPSIS results allows the final priority ranking of technologies for the detection and response to marine oil pollution to be determined, which will be discussed in the results chapter.

The TOPSIS procedure was carried out through five standard steps.

1) Establishment of a normalized decision matrix

$$x'_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{5}$$

where:

- x_{ij} = value of criterion j for paper i
- m = number of papers

2) Calculating weighted decision matrix:

$$v_{ij} = w_j \cdot x'_{ij} \tag{6}$$

where w_j denotes the weight obtained using AHP method.

3) Determining ideal and anti-ideal solutions:

Ideal solution A^+ is defined as the set of the best weighted values for each individual criterion A_j^+, while anti-ideal solution A^- contains the lowest weighted values A_j^-. In this way, the reference best and worst technological profile was defined for the comparison of all ranked papers.

4) Calculating distances from ideals and anti-ideals:

$$d_i^+ = \sqrt{\sum_j \left(v_{ij} - A_j^+\right)^2}, \qquad d_i^- = \sqrt{\sum_j \left(v_{ij} - A_j^-\right)^2} \tag{7}$$

5) Determining rank coefficient (TOPSIS Score):

$$C_i = \frac{d_i^-}{d_i^+ + d_i^-} \tag{8}$$

Values closer to 1 indicate works that are closer to the ideal technological profile.

3. Results and Discussion

The results show that most papers are included within cluster 1 (Conventional SAR/PolSAR), highlighting the dominance of satellite-based approaches in the literature. A relatively large number of papers are also grouped in cluster 6 (AI/data fusion), reflecting the increased use of advanced data processing methods in recent research (Figure 2).

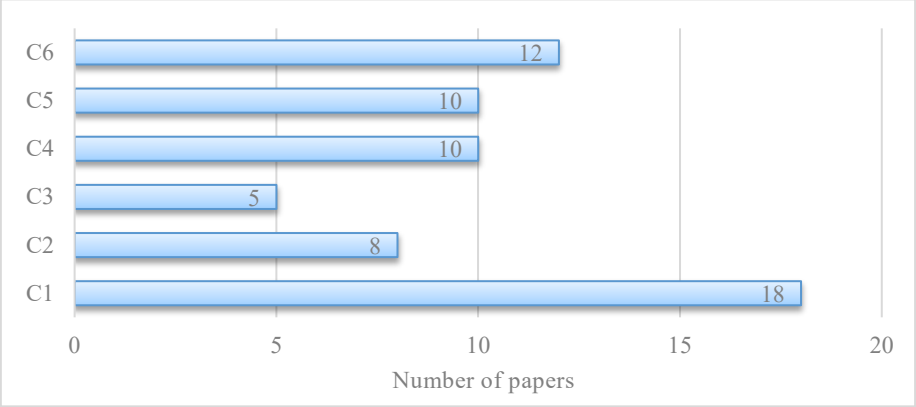


Figure 2. Distribution of papers across technology clusters

AHP weighting (Table 4) showed that Accuracy had the highest relative importance (0.229), followed by Emergency response suitability (0.154), Weather robustness (0.153), and Timeliness (0.153). For n = 8 criteria, the maximum eigenvalue of the pairwise comparison matrix is λmax = 8.15, while the corresponding random consistency index (RI) according to Saaty's scale is 1.41. The resulting consistency ratio was CR = 0.0146, confirming a highly consistent pairwise comparison matrix.

Table 4. Weights obtained by AHP

Criterion	Weight
Accuracy	0.229
Weather robustness	0.153
Timeliness	0.153
Spatial coverage	0.082
Automation	0.112
Emergency	0.154
Maturity	0.069
Recency	0.050

As shown in Table 5, aggregating TOPSIS scores at the level of technology clusters reveals that cluster C6 (AI/deep learning/data fusion) achieves the highest average TOPSIS score (0.523285), although it is less represented in the corpus (12 papers) than cluster C1. Immediately following is C1 (Conventional SAR/PolSAR)

with a very similar average value (0.504169), and this cluster contains the highest-ranked single paper (rank 1). This relationship between the number of papers and the average result indicates that the bibliometric dominance of classical SAR approaches does not necessarily correspond to the highest overall multi-criteria priority, but that modern AI and data-fusion approaches deliver more balanced performance in terms of accuracy, automation, timeliness, and suitability for emergency response.

Cluster C5 (LIF/fluorescence/spectroscopy) ranks third by average score (0.428637), with its median (0.442716) exceeding the average, indicating relatively stable and consistent paper quality within that cluster.

In contrast, clusters C3 and C4 have the lowest average values, indicating limitations in spatial coverage, temporal sensitivity, and local operational range of technologies.

Table 5. Aggregated TOPSIS results for technology clusters

Cluster	Cluster name	N paper	Average TOPSIS	Median TOPSIS	Best Rank
C1	Conventional SAR / PolSAR	18	0.504169	0.489915	1
C2	Optical / hyperspectral / multispectral	8	0.404843	0.397601	23
C3	Thermal infrared / IR polarimetry	5	0.328365	0.307430	43
C4	UAV / ASV / AUV robotic platforms	10	0.368150	0.375967	40
C5	LIF / fluorescence / spectroscopy	10	0.435660	0.441376	13
C6	AI / deep learning / data fusion	12	0.523285	0.485879	2

A small difference between the average and median TOPSIS values for clusters C1 and C6 confirms the uniform ranking of papers within these groups, making the aggregated result representative of the dominant technology profile of the cluster. In contrast, larger deviations in other clusters indicate greater heterogeneity of work, primarily due to the inclusion of secondary and tertiary cluster contributions through 50–50 TOPSIS aggregation. This variability, especially pronounced in hybrid work, further confirms the interdisciplinary nature of modern approaches to the detection of marine oil pollution, where sensor, platform, and AI methods are increasingly combined into single operating systems.

4. CONCLUSION

The main contribution of the paper is the development of an integrated and reproducible methodological framework that links bibliometric analysis, technological grouping, and AHP–TOPSIS multi-criteria ranking for the systematic assessment of modern technologies for detecting marine oil pollution. Using this approach, six technology clusters were identified and ranked based on a combination of operational, automation, and bibliometric criteria.

The results indicate that combining SAR/PolSAR satellite surveillance and AI/data fusion is the most promising direction for developing future systems for early warning and response to oil spills in the marine environment. The synergy between robust all-weather satellite detection with wide coverage and intelligent automated data processing is particularly significant, confirming the shift towards integrated decision-support systems.

One methodological limitation of the research concerns the determination of AHP weights, which were established using the author's expert judgement (decision-maker approach), rather than through consensus from a larger panel of experts. Although this approach is methodologically acceptable and frequently used in AHP–TOPSIS studies, the resulting weights partially reflect the author's interpretative framework, informed by bibliometric analysis, technological literature, and domain knowledge.

Future research could enhance the robustness of the model by involving more experts in satellite surveillance, spill response operations, and autonomous maritime systems, by applying Delphi or group-AHP methods, and by conducting sensitivity analysis of AHP weights and comparative evaluations using alternative

MCDM techniques. Another avenue for development is the validation of the prioritised technologies using real incident scenarios and operational simulators.

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Improvement of Data Processing Algorithms for Enhanced Accuracy of Inertial Navigation Systems

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Abstract: Maritime Autonomous Surface Ships (MASS) require Inertial Navigation Systems (INS) that remain accurate when Global Navigation Satellite System (GNSS) signals are absent or degraded. This paper proposes a three-level hybrid architecture that couples an Unscented Kalman Filter (UKF) with a Transformer-based adaptive covariance estimator and a Long Short-Term Memory (LSTM) error-prediction module, and clarifies the specific contribution this combination makes relative to existing single-level hybrid INS schemes reported in the literature. A structured validation methodology, comprising Monte Carlo simulation, hardware-in-the-loop testing, and staged sea trials, is defined to enable objective verification of the claimed accuracy improvements. The conceptual design and projected performance envelope are presented; full implementation and field validation are identified as the next stage of this research programme.

Keywords: inertial navigation system; Kalman filter; deep learning; Maritime Autonomous Surface Ships; validation methodology

1. Introduction

The development of Maritime Autonomous Surface Ships (MASS) — a term used throughout this paper to denote crewless or remotely supervised surface vessels capable of varying degrees of autonomous operation, and encompassing the smaller class of Unmanned Surface Vehicles (USV) referenced in some cited studies — places increasingly high demands on the accuracy and reliability of navigation systems, especially when GNSS signals are absent or degraded. The International Maritime Organization (IMO) is actively developing mandatory regulations for MASS that must guarantee a level of safety equivalent to or higher than that of conventionally crewed vessels *(GAO, 2024; IMO, 2024)*. This regulatory framework was formally adopted as a non-mandatory instrument at MSC 111 in May 2026 (see Section 8.1) *(IMO, 2026)*.

INS provide continuous navigational information independently of external signals; however, their accuracy is inherently limited by error accumulation due to sensor noise, bias drift, and numerical integration *(Jekeli, 2001)*. Recent research demonstrates that integrating deep learning with traditional filtering algorithms can substantially enhance INS performance *(Chen et al., 2024; Brossard et al., 2024)*.

This paper proposes a three-level hybrid architecture for MASS-borne INS data processing and positions it relative to existing work. The remainder of the paper is structured as follows: Section 2 states the research contribution and novelty of the proposed approach; Section 3 introduces the system architecture; Sections 4–6 describe each functional level; Section 7 addresses computational integration; Section 8 discusses IMO compliance; Section 9 defines the validation methodology; Section 10 reports expected results; Section 11 discusses limitations, and conclusions are drawn in Section 12.

2. Research Contribution and Novelty

Existing hybrid INS/deep-learning frameworks in the literature predominantly address a single point of weakness in the classical Kalman filtering process in isolation. Three such strands can be distinguished: (i) learned process-noise/measurement-noise covariance estimators that replace fixed Q/R tuning, exemplified by Transformer-based approaches such as A-KIT *(Brossard et al., 2024);* (ii) convolutional or recurrent motion-state classifiers used to switch between discrete filter tuning regimes *(Xu et al., 2025);* and (iii) recurrent error-prediction networks, typically LSTM-based, used to bridge GNSS outages by learning the deterministic

component of INS drift *(Brossard et al., 2020; Chen et al., 2024).* To the best of the authors' knowledge, no published maritime INS study combines all three mechanisms within a single coordinated architecture that explicitly separates short-horizon covariance adaptation (Level 2) from long-horizon drift compensation (Level 3) while keeping a conventional UKF (Level 1) as the certifiable, always-available baseline estimator.

What has not been done previously: prior single-level studies report performance gains for one mechanism in isolation, under inconsistent test conditions and sensor suites, which prevents a fair comparison of where each mechanism contributes most. None of the reviewed sources combine adaptive short-term covariance tuning with independent long-term LSTM drift compensation operating on a common UKF state, nor do they specify a fallback mechanism that allows the system to revert automatically to a certifiable conventional UKF if either learned component becomes unreliable.

Why combining these three levels constitutes a contribution: the three mechanisms operate on different time horizons and address different error sources — sensor-level nonlinearity (Level 1), short-term covariance mismatch under changing sea state and manoeuvring (Level 2), and long-term systematic drift during GNSS denial (Level 3). Treating them as a coordinated architecture, with defined hand-off points and a shared fallback policy, is architecturally distinct from applying any one mechanism alone, and is expected to yield complementary rather than redundant error reduction.

How the architecture differs from existing frameworks: unlike A-KIT-type approaches, which adapt Q but leave long-horizon drift uncorrected, and unlike standalone LSTM error-compensation studies, which assume a fixed, non-adaptive UKF baseline, the proposed architecture couples both mechanisms around a common UKF state and innovation sequence, with an explicit anomaly-detection and fallback layer (Section 8.2) absent from the cited single-level studies. The present paper reports the conceptual design, the data flow between levels, and the validation protocol (Section 9) by which this architectural claim can be tested; quantitative results in Section 10 are accordingly presented as projections derived from the literature review and the authors' analysis of each component's reported individual performance, not as results from the integrated system, which is the subject of ongoing implementation.

3. System Architecture

The proposed system comprises three functional levels, each addressing a specific error source in navigational data processing *(Zhou et al., 2024):*

– Level 1: Multi-sensor fusion based on UKF
– Level 2: Adaptive tuning of filter covariance parameters via neural networks
– Level 3: Long-term compensation of systematic errors via LSTM

This hierarchical structure is intended to exploit the advantages of each method while compensating for their respective shortcomings, as set out in Section 2.

4. Level 1 — UKF with Multi-Sensor Fusion

4.1 Theoretical Background

The Unscented Kalman Filter (UKF) is an effective alternative to the Extended Kalman Filter (EKF) for nonlinear systems, using the sigma-point method instead of linearisation to achieve higher accuracy in approximating nonlinear transformations *(Wan and Van der Merwe, 2000).* For maritime applications, motion model nonlinearity is especially pronounced due to wave action, wind, and sea currents.

4.2 Sensor Configuration and the Role of AIS

The primary sensors contributing directly to the UKF state vector are: MEMS IMU (accelerometers and gyroscopes, providing linear acceleration and angular velocity for the prediction step), GNSS (position and velocity updates when available), DVL — Doppler Velocity Log (velocity relative to the seabed, used as a measurement update during GNSS outage), and a magnetic compass (heading reference) *(Liu et al., 2020; Yan et al., 2022).*

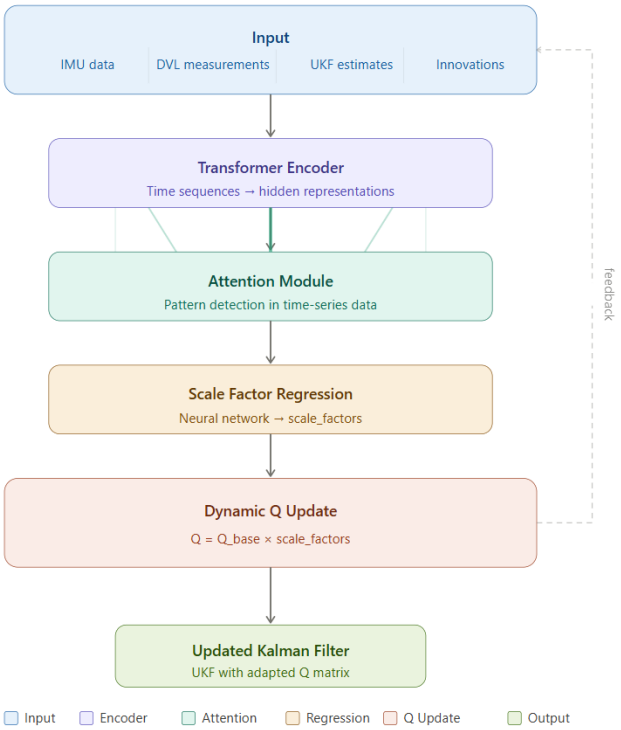


Figure 1. Multi-level hybrid architecture of the INS data processing system for autonomous marine vessels.

The Automatic Identification System (AIS) is included in the sensor suite but is not treated as a primary state-estimation input. AIS broadcasts a vessel's own GNSS-derived position, course, and speed over Very High Frequency (VHF) radio for the purposes of identification, traffic awareness, and collision avoidance; consequently, an own-ship AIS message does not provide an independent measurement of the vessel's state and is not used as a UKF observation. In the proposed architecture, AIS data serve two supporting functions only: (i) plausibility checking, by comparing the own-ship AIS-broadcast position against the UKF estimate as an independent integrity flag when GNSS is available, and (ii) contextual input to the Level 2 motion-state classifier (Section 5.3), where received AIS traffic density and manoeuvring patterns of nearby vessels help characterise the operating environment. AIS is therefore explicitly excluded from the UKF measurement vector and is not credited with any of the accuracy figures reported in Section 10.

4.3 Advantages of UKF for Maritime Navigation

Comparative studies report 20–30% higher accuracy for UKF relative to EKF under significant nonlinearities, improved convergence with uncertain initial conditions, and more stable performance during high-dynamic vessel manoeuvres *(Yuan et al., 2024)*. Liu et al. *(2019)* demonstrated fuzzy adaptive Kalman filtering for Unmanned Surface Vehicles (USV), dynamically adjusting sensor trust weights based on operational conditions; this single-mechanism result motivates, but does not by itself constitute, the three-level architecture proposed here.

5. Level 2 — Adaptive Parameter Tuning via Neural Networks

5.1 Covariance Matrix Estimation Problem

A key challenge in Kalman filtering is the accurate determination of the process-noise covariance matrix Q and measurement-noise covariance matrix R, which in practice vary with vessel dynamics, sea state, and sensor operating mode rather than remaining fixed *(Zhao et al., 2024)*.

5.2 Transformer-Based Covariance Adaptation

The proposed Level 2 module adapts the Adaptive Kalman-Informed Transformer (A-KIT) concept *(Brossard et al., 2024)* to the maritime sensor suite defined in Section 4.2. A Set-Transformer network processes short windows of inertial measurements and UKF innovations; a regression head predicts scale factors for Q, and a Kalman-informed loss function constrains the output to remain consistent with filtering theory. The Q matrix is updated as Q = Q_base × scale_factors at each adaptation cycle.

5.3 CNN-GRU Motion-State Classifier

A CNN-GRU classifier *(Xu et al., 2025)* identifies the vessel motion state — stationary, steady cruise, manoeuvring, or docking — from IMU data augmented with AIS-derived traffic context (Section 4.2), and selects the appropriate Q/R adaptation regime. A convolutional front-end extracts spatial features from the inertial window; a Gated Recurrent Unit (GRU) models temporal dependencies; reported trajectory-accuracy improvement for this mechanism in isolation is approximately 25% relative to a non-adaptive baseline.

6. Level 3 — Long-Term Error Compensation via LSTM

6.1 GNSS-Denied Navigation Problem

During prolonged GNSS absence — passage under bridges, enclosed-water operations, or intentional jamming — pure inertial navigation errors grow quadratically for position and linearly for velocity *(Groves, 2013)*. Even after UKF correction, residual systematic errors continue to accumulate.

6.2 LSTM Error Prediction and Online Adaptation

LSTM networks model long-term temporal dependencies and can learn to predict the deterministic component of INS error *(Brossard et al., 2020; Chen et al., 2024)*. The proposed module comprises two recurrent layers (128 and 64 units) and a fully connected output layer, taking as input the UKF position and velocity deviations, raw IMU readings, temperature, and sea state. When GNSS is available, the network trains on the realised deviation between the UKF estimate and GNSS ground truth; when GNSS is unavailable, the predicted error is subtracted from the UKF estimate. Upon GNSS recovery, incremental weight updates *(Farchi et al., 2023)* adapt the model to the specific vessel and route.

6.3 Reported Results for the LSTM Mechanism in Isolation

Studies of LSTM-based INS error compensation, evaluated as a standalone mechanism rather than as part of a combined system, report *(Chen et al., 2024; Brossard et al., 2020):*

– Short GNSS outages (1–5 min): position error reduced by 40–60%
– Medium outages (5–15 min): improvement of 30–45%
– Long outages (>15 min): improvement of 20–35%

7. Integration of Levels and Computational Efficiency

The three levels are intended to operate synergistically. Raw sensor data feed Level 1 (UKF prediction and update); UKF innovations feed Level 2 (neural estimation of Q and R); the updated UKF state feeds Level 3 (long-term LSTM compensation). The projected update rates are 100 Hz (UKF), 10–20 Hz (adaptive neural network), and 1–5 Hz (LSTM) *(Chen et al., 2024)*.

Target embedded hardware is an ARM Cortex-A53 or NVIDIA Jetson Xavier NX platform, with a design budget of under 10 ms total computational latency per cycle to satisfy real-time requirements for autonomous maritime navigation; this budget has not yet been confirmed on target hardware and is identified as a validation task in Section 9.

8. IMO Compliance and Certification

8.1 Regulatory Context

The non-mandatory International Code of Safety for Maritime Autonomous Surface Ships (MASS Code) was adopted by the IMO Maritime Safety Committee at its 111th session (MSC 111, 13–22 May 2026) and

entered into effect on 1 July 2026 *(IMO, 2026)*. The Code initiates an Experience-Building Phase, during which operational data from MASS deployments will be collected to inform a subsequent mandatory MASS Code, expected to be adopted by 2030 and to enter into force on 1 January 2032 *(IMO, 2026)*. Key requirements of the non-mandatory Code include safety equivalence, redundancy, verifiability, and fault tolerance. DNV and other classification societies have in parallel developed AROS (Autonomous and Remotely Operated Ships) notations establishing technical standards, including positioning accuracy better than 10 m (95% of the time) without GNSS, a minimum of two independent navigation systems, data integrity, and cybersecurity provisions *(DNV, 2024a; DNV, 2024b)*.

8.2 Compliance Strategy and Fallback

The proposed architecture is designed to satisfy these requirements *(Mu et al., 2025)* through the following measures: UKF multi-sensor fusion provides redundancy across heterogeneous sensors; the Level 2 and Level 3 learned components improve accuracy over a non-adaptive baseline; continuous monitoring of UKF innovations against a χ^2-consistency test detects anomalous filter behaviour; and the system automatically reverts to the conventional, non-adaptive UKF of Level 1 whenever either learned module is flagged as unreliable, preserving a certifiable fallback mode at all times.

9. Validation Methodology

To enable objective verification of the performance claims in Section 10, a three-stage validation protocol is defined, progressing from controlled simulation to sea trials. No stage has yet been executed in full; the protocol below specifies what is required before the performance figures in this paper can be treated as validated results rather than projections from the literature.

9.1 Stage 1 — Monte Carlo Simulation

A six-degree-of-freedom vessel motion simulator will generate reference trajectories representative of typical MASS operating profiles (steady transit, manoeuvring, docking), with synthetic IMU, DVL, and GNSS measurements corrupted by sensor-realistic noise models. Scripted GNSS outages of 1, 5, 15, and 30 minutes will be injected at random points in each run. A minimum of 500 Monte Carlo runs per scenario is specified to obtain statistically stable estimates of position, velocity, and heading error distributions, with the proposed architecture compared against a non-adaptive UKF baseline and against each learned component evaluated in isolation, to attribute accuracy gains to specific levels of the architecture.

9.2 Stage 2 — Hardware-in-the-Loop Testing

The trained Level 2 and Level 3 networks will be deployed on the target embedded platform (Section 7) and exercised with recorded sensor logs replayed in real time, to verify the 10 ms per-cycle latency budget under realistic computational load and to confirm that the fallback mechanism of Section 8.2 triggers correctly under injected sensor faults and adversarial innovation sequences.

9.3 Stage 3 — Sea Trials

Given the practical, legal, and safety constraints of testing an unproven navigation system at sea, Stage 3 is structured as two sequential phases of increasing operational risk rather than a single open-sea campaign. Active radio-frequency jamming of GNSS is restricted or prohibited in most jurisdictions and is not proposed here; GNSS denial is instead emulated by physically shielding or disconnecting the GNSS antenna on the test platform, a method consistent with guidance for trials of remotely operated and autonomous vessels *(Indian Register of Shipping, 2022)*. The first phase will be conducted on a small instrumented test craft in sheltered, low-traffic waters such as a harbour basin or marina, under direct visual control and with a safety boat in attendance, using a survey-grade GNSS/INS unit logging continuously as ground truth. This phase focuses on short, repeatable GNSS-denial runs (1–5 minutes) under benign sea states, allowing the Level 2 and Level 3 modules and the Level 1 fallback mechanism (Section 8.2) to be exercised and debugged at low operational risk before exposure to open-water conditions, and is estimated to require 4–6 months, allowing for vessel and instrumentation availability, mooring and harbour-authority permissions, and repeated test runs needed to characterise the system under varying numbers of visible satellites and multipath conditions typical of harbour

environments. Subject to satisfactory completion of this first phase, trials will progress to coastal waters with prior notification to the relevant maritime authority, using a larger instrumented vessel more representative of a MASS-scale platform; GNSS-denial periods will be extended to the 5–30 minute range used in Stage 1, executed only in weather windows and traffic conditions assessed as low-risk by the trial safety plan, with this second phase estimated at a further 6–9 months given dependence on vessel charter availability, suitable weather windows, and authority approval — giving a combined Stage 3 duration of approximately 10–15 months rather than the 1–2 months assumed in earlier planning estimates for this paper. Acceptance is assessed separately for each phase rather than as a single pass/fail threshold: the sheltered-water phase is considered successful if the system completes all scheduled GNSS-denial runs without an uncommanded fallback failure and with position error trends consistent with the Stage 1 simulation results, and progression to the coastal phase, and ultimately comparison against the AROS-aligned target of position error below 5 m during 5-minute GNSS outages referenced in Section 8.1, is conditional on that outcome; the 95% trial-run success figure should accordingly be read as a target for a mature test campaign rather than an expectation for the first coastal trials.

10. Expected Results

The figures below are projections derived from the individual, isolated performance of each mechanism as reported in the cited literature *(Chen et al., 2024; Brossard et al., 2024; Liu et al., 2019; Brossard et al., 2020),* combined under the assumption of complementary, non-overlapping error reduction across levels; they are not yet results from the integrated, implemented system, which remains to be confirmed through the validation programme of Section 9:

– GNSS outage 1–5 min: projected position error <5 m (baseline UKF: ~15 m)
– GNSS outage 5–15 min: projected position error <20 m (baseline UKF: ~100 m)
– GNSS outage 15–30 min: projected position error <50 m (baseline UKF: >500 m)
– Velocity accuracy: ±0.1 m/s (baseline UKF: ±0.3 m/s)
– Heading accuracy: ±1° across all operating modes (baseline UKF: ±3°)
– Computational latency target: <10 ms per cycle on NVIDIA Jetson Xavier NX (design budget, not yet measured)

11. Advantages, Limitations and Mitigation

Potential advantages of the proposed combination include higher accuracy than any single mechanism applied alone, adaptability to varying operating conditions, robustness against individual sensor failures through the Level 1 fallback, and scalability to additional sensor types.

The principal limitation of the present paper, acknowledged directly, is that it synthesises and architecturally combines methods validated individually in the literature rather than presenting results from an implemented and field-tested system; Section 9 specifies the protocol by which this limitation is to be addressed in subsequent work. Further limitations include increased computational requirements relative to a non-adaptive UKF, dependency on high-quality training data for the Level 2 and Level 3 networks, limited interpretability of the learned components, and the need for certification of the machine-learning modules by classification societies before operational deployment *(DNV, 2024a; DNV, 2024b).*

12. Conclusions

This paper has proposed a three-level hybrid architecture for MASS INS data processing, combining a conventional UKF baseline with a Transformer-based covariance adaptation module and an LSTM long-term error-compensation module. Section 2 set out the specific respects in which combining these three mechanisms within one coordinated architecture, with an explicit fallback policy, differs from existing single-mechanism hybrid INS studies; Section 9 defined a three-stage validation protocol — Monte Carlo simulation, hardware-in-the-loop testing, and instrumented sea trials — by which the projected accuracy figures of Section 10 are to be independently confirmed.

Execution of this validation programme, and reporting of measured (rather than projected) accuracy, latency, and reliability figures, is identified as the necessary next stage of this research before the system can

be considered ready for operational deployment in support of safer autonomous vessel navigation under the newly adopted IMO MASS Code.

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Integrating Cognitive Bias into HFACS for Maritime Accident Analysis: Evidence from the Bosphorus Tanker Collision

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Abstract: This study proposes an integrated methodological framework that combines the Human Factors Analysis and Classification System (HFACS) with structured cognitive bias mapping to enhance causal analysis in maritime accident investigations. The framework extends conventional HFACS application by explicitly incorporating cognitive mechanisms that influence operational decision-making under conditions of uncertainty, stress, and environmental constraints. A retrospective qualitative case study design was applied using a tanker collision in the Bosphorus Strait as an empirical validation case. The analysis used the DoD HFACS 8.0 taxonomy alongside a systematic protocol for identifying cognitive biases. Five maritime subject-matter experts independently coded fifteen operational events, and an inter-rater reliability assessment was conducted to evaluate consistency in classification. The integrated analysis demonstrated that cognitive biases function as mediating mechanisms, linking systemic conditions, and unsafe acts. Unsafe Acts and Preconditions were the most frequently identified HFACS categories, particularly delayed maneuvering, excessive speed, degraded situational awareness, and procedural fixation. Cognitive bias mapping identified overconfidence bias, confirmation bias, the authority gradient, and the normalization of deviance as key contributors to navigational judgment and action selection. The proposed framework improves explanatory depth, causal transparency, and analytical resolution compared to traditional HFACS applications. The model provides a structured and reproducible method for identifying cognitive-system interactions. This approach supports the development of targeted safety interventions, training programs, and safety management strategies for operations in constrained and high-risk maritime environments.

Keywords: Human factors; HFACS; Maritime accident; Cognitive bias; Navigation safety

1. Introduction

Despite technological progress, human error remains the primary cause of maritime accidents in constrained waterways (Reason James, 1997; Martins and Maturana, 2010). While the Human Factors Analysis and Classification System (HFACS) effectively categorize unsafe acts and organizational failures (Wiegmann and Shappell, 2001) it often fails to explain the underlying cognitive mechanisms of operator decision-making. Cognitive psychology suggests that systematic biases significantly distort risk perception and situational awareness under uncertainty (Kahneman, 2011). However, these biases are rarely formalized in maritime accident frameworks. This paper addresses this gap by integrating a cognitive bias framework into HFACS. Through a case study of the *MT Petar Zoranić* and *MT World Harmony* collision in the Bosphorus, this research demonstrates how cognitive biases mediate the relationship between environmental stressors and unsafe operational behavior in narrow channels.

2. Literature Review

Human error is widely recognized as a primary factor in maritime accidents (Reason James, 1997) Accidents result from interactions between active failures and latent organizational conditions. Studies confirm that decision-making errors and loss of situational awareness are dominant contributors in collisions and groundings (Martins and Maturana, 2010).

2.1 HFACS in Maritime Accident Analysis

HFACS categorized contributing factors into four levels: unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences. It is widely applied in maritime accident analysis to identify human and systemic factors (Celik, Lavasani and Wang, 2010). However, several authors have noted that HFACS remains largely descriptive and does not explicitly address the cognitive mechanisms underlying decision-making errors (Salmon, Cornelissen and Trotter, 2012). As a result, HFACS analyses may identify failures without explaining why operators persisted in unsafe strategies despite available corrective cues.

2.2 Cognitive Biases in Safety-Critical Systems

Cognitive biases are systematic deviations from rational judgment that arise when individuals rely on heuristic-based reasoning under uncertainty and time pressure (Kahneman, 2011) between fast, intuitive thinking and slower, analytical reasoning, noting that the former dominates under stress. In safety-critical domains, biases such as overconfidence, confirmation bias, authority gradient, and procedural fixation have been shown to impair error detection and recovery (Reason James, 1997). Despite their relevance, cognitive biases remain underrepresented in formal maritime accident investigation methodologies.

3. Case Overview

The collision occurred in the Bosphorus Strait, a constrained waterway with strong currents and dense traffic. At the time of the accident, a 5 knot reverse current (*Orkoz*) significantly affected vessel maneuverability. A mixed navigation regime combining local left-hand rules and international right-hand navigation created regulatory ambiguity and increased operational complexity.The combination of incorrect vessel positioning, reduced reaction time and conflicting navigational expectations resulted in a collision between *MT Petar Zoranić* and *MT World Harmony* followed by explosion, causing significant loss of life.

4. Methodology

The methodology integrates accident reconstruction, HFACS-based coding, inter-rater reliability assessment, and cognitive bias analysis to enhance causal interpretation (Reason James, 1997; Celik, Lavasani and Wang, 2010). To enhance the explanatory depth of the HFACS-based analysis, a cognitive bias framework was incorporated into the methodological design. Cognitive biases were examined as underlying psychological mechanisms mediating between environmental stressors, organizational conditions, and observable unsafe acts. Following the initial HFACS classification, identified contributing factors were systematically reviewed and mapped to dominant cognitive biases based on established cognitive psychology and human factors literature (Reason James, 1997; Kahneman, 2011) extending conventional HFACS analysis beyond descriptive categorization toward an interpretative mechanism-based framework. This mapping process aimed to identify recurring patterns of distorted judgment associated with navigational decision-making under operational stress. The analysis follows three stages: identification of operational stressors, mapping of HFACS findings to dominant cognitive biases and validation of consistency within an integrated casual framework. The cognitive bias analysis was conducted qualitatively, as quantitative psychological measurements were unavailable for historical accident cases. This qualitative approach is consistent with previous human factors of research examining decision-making in safety-critical systems. The objective was not to quantify psychological effects, but to identify systematic cognitive mechanisms influencing operational behavior. Through this procedure, cognitive biases were operationalized as interpretative constructs linking latent conditions and active failures within the HFACS framework.

4.1. Data sources and accident reconstruction

Primary data sources included archival accident reports, historical navigation records, contemporaneous regulatory documents, and secondary literature describing hydrodynamic conditions and navigational practices in the Bosphorus during the period. Operational sequences were reconstructed based on available timelines, vessel trajectories, witness testimonies, and documented environmental conditions. Given the absence of electronic navigation recordings, the reconstruction focused on observable operational actions, documented

procedural requirements, and plausible decision- making sequences supported by established maritime practice and human factors theory.

4.2. HFACS taxonomy and coding procedure

The Department of Defense HFACS version 8.0 taxonomy was selected due to its expanded hierarchical structure and incorporation of nano-codes addressing cognitive processing, risk perception, and organizational dynamics(Wiegmann and Shappell, 2001). The taxonomy as per Figure 1, classifies contributing factors across four system levels: Unsafe Acts, Preconditions for Unsafe Acts, Unsafe Supervision, and Organizational Influences. Identified events, decisions, and contextual factors were systematically mapped to HFACS categories and nano-codes using expert judgment. Coding focused on documented operational actions, regulatory deviations, environmental constraints, and supervisory and organizational practices (Bilbro, 2013) To reduce interpretative bias, ambiguous factors were classified conservatively and only when supported by multiple independent sources or established causal mechanisms (Griggs, 2012).

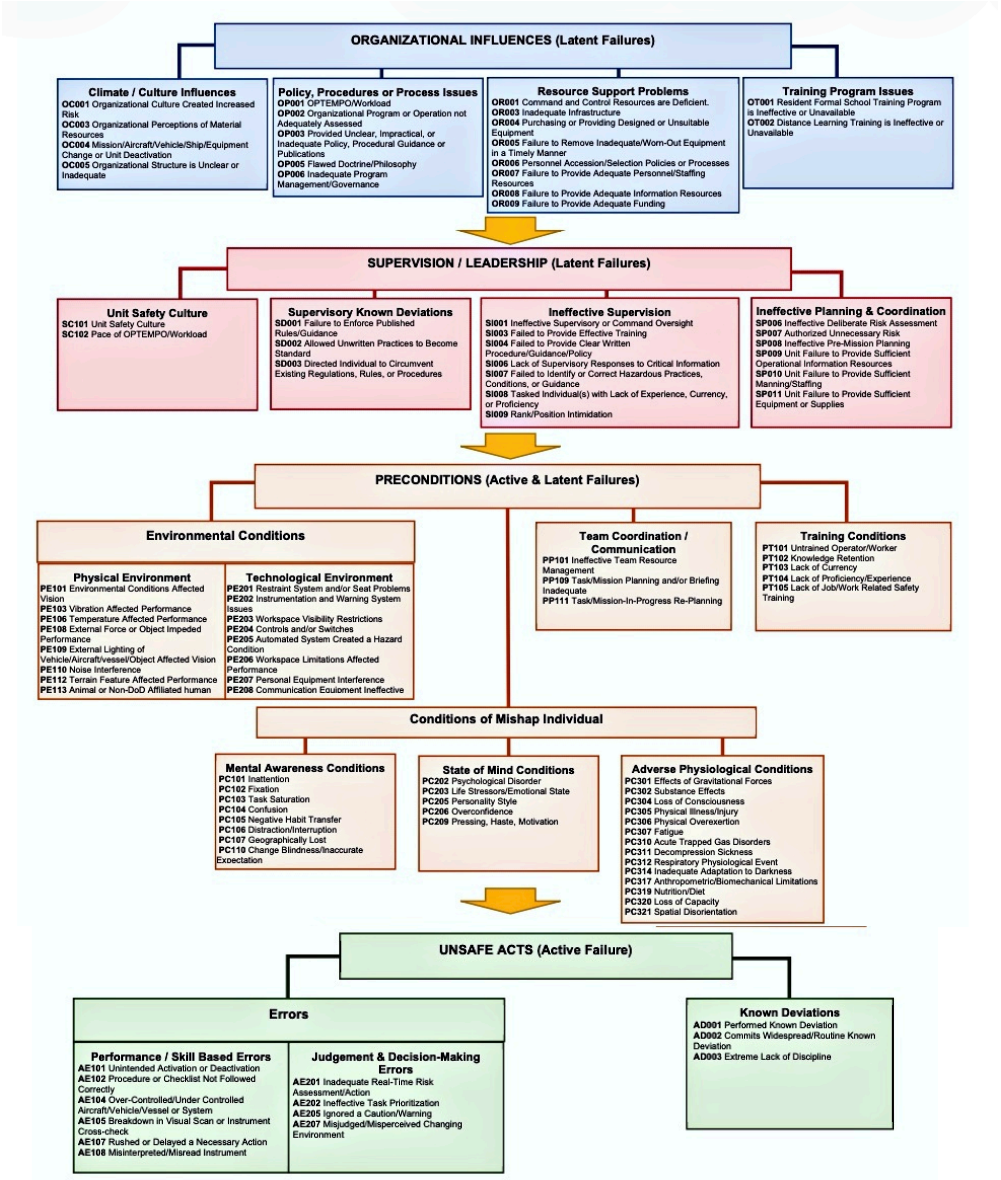


Figure 1. HFACS DoD nano-codes. Source: U.S. Department of Defense Human Factors Analysis and Classification System (DoD HFACS) version 8.0 (2022), page 33

4.3. Inter-rater reliability assessment (Fleiss' Kappa)

To assess the reliability of the HFACS classification, an inter-rater agreement analysis was conducted using Fleiss' Kappa coefficient. A panel of raters consisting of five maritime experts and experienced navigation officers independently classified a predefined set of critical operational events and causal factors using the HFACS taxonomy. Prior to coding, all raters received standardized explanation on HFACS structure, coding principles, and category definitions. Each rater independently assigned HFACS codes to the same set of events. Agreement levels were calculated for overall classification and for individual HFACS levels using Fleiss' Kappa statistic. Kappa values were interpreted according to the criteria proposed by Landis and Koch, (Landis and Koch, 1977) where values below 0.20 indicate slight agreement, 0.21–0.40 fair agreement, 0.41–0.60 moderate agreement, 0.61– 0.80 substantial agreement, and values above 0.81 almost perfect agreement.

4.4 Cognitive Bias Analysis Procedure

Expanding the traditional HFACS framework, this study incorporates a structured cognitive bias analysis to elucidate the systematic judgment distortions influencing navigational decision-making under operational stress. By synthesizing HFACS classifications with cognitive psychology and human error theory, this research maps contributing factors such as situational awareness, communication, and procedural compliance to specific cognitive mechanisms. framework. Cognitive bias identification was performed only after the HFACS classification had been completed. The assignment procedure consisted of three consecutive stages: (1) identification of HFACS contributing factors, (2) mapping these factors to established cognitive biases using cognitive psychology and human factors literature, and (3) expert review to ensure theoretical consistency and interpretative coherence. The identified biases represent an analytical interpretation of decision-making mechanisms rather than a direct psychological diagnosis.

5. Results

The HFACS analysis revealed contributing factors distributed across all system levels. Unsafe acts primarily involved speed mismanagement and delayed maneuver initiation. Preconditions were dominated by environmental misjudgment and situational awareness of degradation. Supervisory deficiencies and organizational shortcomings shaped the operational context in which unsafe acts emerged. Based on the HFACS classification and operational reconstruction, fifteen key findings were identified:

- Procedural non-compliance (AE102): Failure to follow left-hand navigation protocol, resulting in incorrect vessel positioning
- Regulatory Enforcement Failure (SD001): Decision to transit without a pilot under constrained and high-risk conditions
- Command Overconfidence (PC206): Despite limited experience in the Strait (one year), the Master of the World Harmony elected to transit at night without a pilot, bypassing a critical risk-mitigation resource used by the Petar Zoranić.
- Ineffective Organizational Risk Perception (OC003): Acceptance of high-speed, unpiloted night navigation in a narrow channel
- Environmental Underestimation of the impact of strong reverse current "Orkoz" on maneuverability
- Excessive Speed & Loss of Control (AE104): High speed reduced available reaction time in confined waterway
- Cognitive Confusion (PC104): The coexistence of international "right-hand" and local "left-hand" rules led to a fundamental misperception by the World Harmony's bridge team regarding the expected passing side.
- Inadequate Real-Time Risk Assessment (AE201): Failure to account for navigational constraints imposed by surrounding traffic
- Failure of Bridge Team Management (SI007): Inability to detect and correct unsafe navigation practices

- Delayed Emergency Response (AE107): Late execution of evasive maneuver due to incorrect assumption about the opposite vessel
- Communication Breakdown (AE205): The World Harmony ignored or failed to detect the emergency signals initiated by the Zoranic's pilot, indicating a critical failure in external situational awareness.
- Loss of Situational Awareness (PC101): Reduced perception and processing of navigation cues under high workload
- Deliberate Procedural Deviation (AD001): Intentional deviation from local navigational **r**ules
- Misperception of Closure Rates (AE207): Incorrect estimation of approach speed and safe passing distance
- Authority Gradient Issues (PC205): Lack of corrective intervention by the Officer of the Watch (OOW) due to hierarchical constraints within the bridge team

5.1. Inter-rater reliability

Inter-rater reliability analysis produced a Fleiss Kappa value of 0.45, indicating moderate agreement and acceptable classification consistency. Key findings included delayed maneuver initiation, inappropriate lateral positioning within the channel, excessive speed, ineffective communication, and misinterpretation of navigational rules. These results provide the empirical foundation for subsequent cognitive bias of interpretation. The distribution of identified contributing factors is summarized in Table 1.

Table 1 Distribution of contributing factors across HFACS levels. Source: Author's work

FINDINGS															
Participants	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	AE 102	SD 001	PC 104	OC 003	PE 108	AE 104	SP 008	AE 201	SI 006	AE 107	AE 205	SP 009	AD 001	SP 006	PC 205
2	AD 001	SD 001	PC 206	AE 201	PE 108	AE 207	PC 104	AE 201	SI 001	AE 107	AE 205	PC 101	AD 002	AE 207	PC 205
3	AE 102	OP 002	PC 206	OC 003	PE 108	AE 207	PC 107	AE 201	SI 001	AE 107	AE 205	PC 101	AE 102	AE 207	PC 205
4	AE 102	SD 001	PC 320	0C 003	PE 108	AE 104	PC 104	AE 201	SI 001	AE 201	AE 205	PC 101	AD 001	AE 207	PC 205
5	AE 207	SD 003	PC 206	0C 003	PE 108	AE 104	PC 104	AE 104	SI 009	AE 107	AE 205	AE 201	AD 001	PC 203	SI 001

Table 1 displays the distribution of HFACS nano-codes assigned by five independent raters across fifteen key accident observations, adhering to the DoD HFACS taxonomy to ensure robust assessment and minimize bias. The data provides the empirical basis for Fleiss Kappa inter-rater reliability analysis, indicating consistent coding patterns that identify dominant contributing factors and validate the overall accident analysis

5.2 Cognitive Bias Integration in HFACS-Based Accident Analysis

The following analysis interprets identified HFACS factors through a cognitive bias framework. Integrating cognitive bias theory into HFACS enhances explanatory depth by explicitly linking psychological mechanisms to systemic vulnerabilities. In maritime navigation, particularly in constrained waterways, bridge teams operate under high cognitive workload caused by restricted maneuvering space, strong environmental forces, dense traffic, and regulatory complexity. Under such conditions, operators frequently rely on intuitive, experience-based decision-making rather than analytical reasoning. While this heuristic-based approach enables rapid responses, it also increases susceptibility to cognitive biases applicable to the Bosphorus Collision

Phase 1: Contextual Stressors

- Night navigation
- Reverse current (Orkoz)

- Narrow channel geometry
- Absence of pilotage
- Anchored vessel constraint

These factors generated a high cognitive workload

Phase 2: Bias Activation

- Overconfidence reduced perceived risk.
- Confirmation bias filtered warning signals.
- Procedural fixation reinforced incorrect rules of interpretation.
- Authority gradient inhibited corrective intervention.

Phase 3: Decision Degradation

- Delayed maneuver initiation
- Inappropriate lateral positioning
- Excessive speed
- Ineffective communication

Phase 4: System Failure The convergence of biased decisions and environmental constraints produced a head-on collision scenario with an insufficient recovery margin.

6. Discussion

The HFACS analysis indicates a clear dominance of Unsafe Acts and Preconditions for Unsafe Acts in the development of the Bosphorus collision. Excessive speed, delayed maneuver initiation, degraded situational awareness, and procedural deviations emerged as the most influential operational factors, highlighting the critical role of frontline decision-making in constrained navigational environments. Preconditions such as high cognitive workload, environmental misjudgment, and communication limitations suggest that unsafe acts developed within a complex operational context rather than in isolation. Strong reverse currents, regulatory ambiguity, and restricted maneuvering space significantly reduced the bridge team's capacity to detect, interpret, and respond to emerging hazards.

Table 2 Distribution of HFACS nano-codes identified by individual raters and their association with dominant cognitive bias. Source: Author's work.

HFACS Code	Operational Factor	Associated Cognitive Bias
PC 206	Overconfidence	Overconfidence bias
PC 101	Safety awareness loss	Confirmation bias
PC 205	Authority	Authority gradient
PC 104	Rule confusion	Fixation bias
AD 001	Deviation	Normalization
AE 205	Communication failure	Attention bias

Table 2 correlates HFACS nano-codes with dominant cognitive biases, elucidating the psychological mechanisms driving decision-making in constrained navigation. Key findings demonstrate that overconfidence (PC206) leads to overestimated maneuverability, while confirmation bias (PC101) degrades situational awareness through selective cue interpretation. Authority gradient (PC205) inhibits corrective interventions, and fixation bias (PC104) stems from regulatory complexity. Furthermore, normalization of deviance (AD001) reflects incremental procedural erosion, while attentional bias (AE205) underpins communication failures. These results argue that HFACS-identified unsafe acts are fundamentally cognitive; integrating bias analysis provides the necessary explanatory depth to link latent systemic factors with observable operational errors in maritime accident causation.

6.1 Reliability and Interpretative Validity of Findings

The reliability of the findings is supported by the involvement of five independent maritime safety experts who conducted HFACS coding independently, enhancing analytical objectivity. Inter-rater agreement, assessed using Fleiss' Kappa, yielded a value of 0.45, indicating moderate reliability. Although the obtained Fleiss' Kappa indicates moderate agreement, this level of reliability is considered acceptable for retrospective accident investigations based on historical documentation. The absence of direct participant interviews and complete operational records inevitably increases interpretative variability. Future studies may further improve inter-rater reliability through standardized coding protocols, larger expert panels, structured evaluator training, and validation using multiple contemporary accident cases. Given the retrospective nature of the study and limited availability of operational data, this level of agreement is consistent with previous HFACS-based investigations. Subsequent consensus-based review of classification discrepancies further improved internal consistency and interpretative coherence. The convergence of independent assessments and contextual evidence supports the validity of the identified human and organizational factor patterns.

6.2 Cognitive bias Analysis Procedure

The integration of cognitive bias analysis into the HFACS framework enhanced explanatory depth by linking environmental and organizational stressors to unsafe operational behavior. The procedure enabled systematic identification of dominant judgment distortions influencing navigational decisions, including overconfidence, confirmation bias, procedural fixation, and authority gradient. These biases contributed to risk underestimation, selective interpretation of situational cues, and reduced adaptive response under high workload and time pressure. The structured mapping of HFACS findings to cognitive mechanisms improved interpretative coherence and reduced analytical subjectivity. The methodology followed defined stages of stressor identification, bias activation, and performance degradation, ensuring consistency across evaluators. Despite the limitations of retrospective analysis, the convergence of operational evidence, expert assessment, and established cognitive theory supports the validity of the identified bias patterns. The results demonstrate that cognitive bias analysis provides a valuable complement to conventional HFACS classification in constrained maritime environments. The proposed causal structure is illustrated in Figure 3.

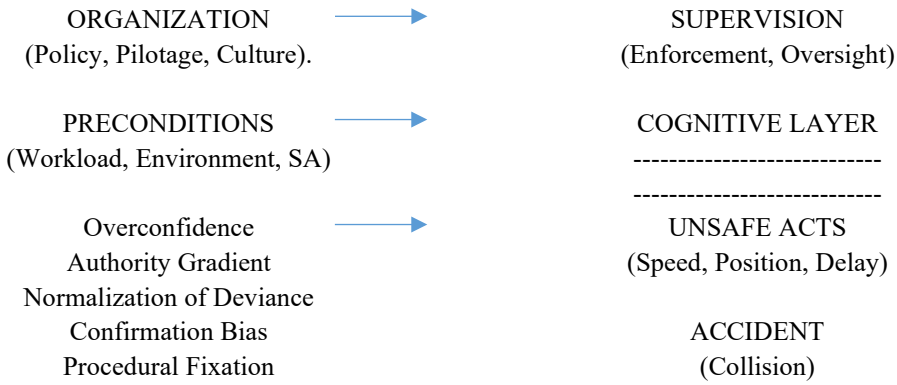


Figure 3 Integrated HFACS-Cognitive Bias-Accident Causation Model. Source: Author's work

Figure 3 illustrates the hierarchical causal structure of the HFACS framework, wherein latent organizational factors—such as regulatory frameworks and safety culture—undermine supervisory effectiveness and allow risks to persist. These systemic deficiencies create preconditions characterized by high cognitive workload and environmental complexity, triggering cognitive biases (e.g., confirmation bias and procedural fixation) that impair situational awareness. Consequently, these distortions manifest as unsafe acts, including maneuver delays and excessive speed, culminating in maritime accidents through a multi-level, systemic progression.

7. Conclusion

This study validates integrating cognitive bias assessment into the DoD HFACS framework via the Bosphorus tanker collision analysis. Results highlight how environmental complexity and regulatory ambiguity interact with systemic judgment distortions—notably overconfidence and confirmation bias—to precipitate unsafe acts like delayed maneuvering and excessive speed. By elucidating the mediating role of these biases, the framework enhances causal transparency beyond traditional descriptive methods. Practically, these findings support revising pilotage policies and incorporating bias-driven scenarios into Bridge Resource Management (BRM) training to bolster navigational resilience. Although demonstrated using a historical accident, the proposed HFACS–cognitive bias framework is equally applicable to modern maritime operations. Increasing levels of bridge automation, integrated navigation systems, ECDIS, autonomous decision-support technologies, and complex traffic environments make systematic assessment of cognitive biases increasingly relevant for contemporary accident investigation and safety management. Ultimately, this psychologically informed approach evolves maritime safety analysis toward more proactive, actionable investigation practices

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State of Charge Estimation for Smart Buoy Battery Systems: Classical vs. Deep Learning Approach

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Abstract: Smart buoys are an important component of modern marine environmental monitoring and navigation safety systems, where reliable autonomous operation depends on efficient energy management. As these systems typically operate off-grid and under highly variable environmental conditions, accurate estimation of battery State of Charge (SoC) is essential for long-term reliability and efficient use of available energy.
This paper investigates the potential of deep learning (DL) to improve SoC estimation in smart buoys by comparing the classical Coulomb Counting (CC) method with a DL-based Long Short-Term Memory (LSTM) approach. The analysis was conducted in MATLAB under three operating regimes representing typical smart buoy conditions: stable sunny operation, reduced solar generation, and increased communication load. Both methods were tested under identical conditions, using the same input data, measurement noise, and reference SoC values obtained from an ideal battery model. Estimation accuracy was evaluated using Root Mean Squared Error (RMSE). The results show that the LSTM-based method consistently achieved lower RMSE values than CC across all tested regimes. The average RMSE decreased from approximately 0.037 for the CC method to 0.005 for the LSTM model, corresponding to an average error reduction of about 84.6%. The maximum LSTM inference time was 0.039 s, which is less than 0.4% of the 10 s sampling interval used in the simulation. Its advantage was particularly evident under variable energy conditions, where CC was more affected by cumulative estimation errors. These findings highlight the suitability of DL for improving SoC estimation and energy management in smart buoy systems.

Keywords: smart buoy; state of charge; Coulomb counting; deep learning; energy management

1. Introduction

Autonomous marine monitoring systems, particularly smart buoys, are essential to modern oceanographic research, environmental protection, and maritime navigation safety. These platforms must operate reliably in remote and challenging marine environments, relying on self-sustaining energy systems and robust Battery Management Systems (BMS) (Bojic *et al.*, 2021; Madani *et al.*, 2025). These platforms play a crucial role in oil spill detection and tracking, as timely data on current speed and wind direction are essential for predicting the movement of pollutants(Tsvetkov and Alexandrov, 2016). Continuous operation depends on accurate State of Charge (SoC) estimation, which prevents power failures and optimises the lifespan of onboard lithium-ion (Li-ion) batteries (Madani *et al.*, 2025). However, estimating the SoC for smart buoys presents unique challenges compared to conventional applications. Unlike Electric Vehicles (EVs) or consumer electronics, which have relatively predictable charge and discharge cycles (Zhang *et al.*, 2022), smart buoys operate under highly stochastic energy conditions (Salmeri *et al.*, 2025). This is primarily due to intermittent energy harvesting while subjecting the battery to irregular discharge pulses dictated by sensor sampling and data transmission telemetry(Salmeri *et al.*, 2025). The sensor payload often includes complex instruments for measuring pressure, conductivity, salinity, dissolved oxygen, pH, and turbidity (Tsvetkov and Alexandrov, 2016). As a result, the non-linear dynamics of the battery are intensified by extreme temperature fluctuations and unpredictable operational loads(Zhang *et al.*, 2022; Madani *et al.*, 2025). Despite significant advancements in SoC estimation techniques, a critical research gap remains regarding the comparative performance of algorithms specifically tailored for autonomous surface marine platforms (Madani *et al.*, 2025). The current literature frequently examines advanced filtering methods for underwater vehicles (Fu *et al.*, 2022) or computationally intensive deep learning (DL) methodologies developed mainly for the EV sector(Zhang *et al.*, 2022). In practical smart

buoy applications, severe hardware and energy constraints mean that foundational classical methods such as Columb Counting (CC), an ampere-hour integration, remain highly relevant. However, CC is particularly susceptible to cumulative sensor error (drift) over time, especially under extreme marine conditions (Zhang *et al.*, 2022). There is a lack of comprehensive studies evaluating the precise trade-off between the low computational footprint of CC and the high accuracy, but high energy overhead, of modern DL approaches in a marine context.

This paper aims to develop a DL model for SoC estimation in smart buoy battery systems and to assess its accuracy by comparison with the classical Coulomb Counting method under irregular load profiles and variable energy conditions. Furthermore, the research assesses how the cumulative drift of CC compares to the stability of DL under simulated marine environmental conditions, with particular attention to diurnal temperature fluctuations, sensor measurement noise, and intermittent solar energy harvesting. Ultimately, this work evaluates the trade-off between estimation precision and algorithmic execution cost to determine the viability of these models for low-power edge computing. The remainder of this paper is organised as follows: Section 2 reviews the background research and related work. Section 3 details the methodology, including data acquisition and model architectures. Section 4 presents comparative results and discussion, while Section 5 concludes the paper.

2. Background Research

To ensure a comprehensive and up-to-date analysis of the state-of-the-art, the literature review for this study was based on a targeted search of the Web of Science and Scopus databases. To identify research at the intersection of autonomous marine platforms and energy storage, the combination of the following keywords was used: “smart buoy”, “Battery Management Systems”, and “State of Charge”. The scope was restricted to peer-reviewed articles published within the last five years to capture the most recent advancements in these fields. The searches were conducted in January 2026.

Recent studies emphasize the growing need for autonomous marine platforms to adopt eco-design principles and robust monitoring frameworks to ensure long-term environmental performance. The transition towards compact and autonomous marine monitoring platforms increases the importance of intelligent energy management and high-performance battery systems (Salmeri *et al.*, 2025). Similarly, the integration of automated smart buoys has been shown to significantly improve navigation safety and environmental monitoring in coastal and port areas. Automated smart buoys are described as three-layer Internet of Things (IoT) systems consisting of sensor, communication, and application layers, highlighting energy-efficient operation and autonomous sampling control as key requirements for reliable deployment (Bojic *et al.*, 2021). These findings indicate that the operational reliability of smart buoys depends not only on sensing capabilities but also on the BMS's ability to adapt energy consumption to changing environmental and operational conditions. The importance of advanced energy management is further supported by another group of authors (Tsvetkov and Alexandrov, 2016), who developed a MATLAB-based simulator for marine monitoring platforms to test monitoring and data management systems before deployment. Their work demonstrates that different monitoring tasks can generate highly variable energy demands, reinforcing the need for accurate battery state monitoring and control. Consequently, extensive research has focused on SoC estimation for Li-ion batteries. Classical methods, such as CC, estimate SoC by integrating battery current over time and remain widely used because of their simplicity and low computational requirements (Zhang *et al.*, 2022; Madani *et al.*, 2025). However, their accuracy depends on precise initialization and is affected by cumulative sensor errors (Zhang *et al.*, 2022). To address these limitations in marine environments, a group of authors (Fu *et al.*, 2022) proposed an Adaptive Iterative Extended Kalman Filter (AIEKF) based on a second-order RC-equivalent circuit model and online parameter identification, achieving improved estimation accuracy and robustness to noise compared with conventional EKF approaches. Nevertheless, model-based methods still require accurate battery modelling and parameter updating under changing operating conditions. To overcome these constraints, recent research has increasingly explored data-driven approaches based on Artificial Intelligence (AI) and DL. In one study, authors (Zhang *et al.*, 2022)systematically classified DL-based SoC estimation methods into single, hybrid, and trans-structures, showing that hybrid architectures combining convolutional and recurrent neural networks can improve estimation accuracy by simultaneously capturing spatial and temporal battery characteristics. This trend towards intelligent battery management is further extended by group of authors

(Madani *et al.*, 2025), who investigated the integration of AI and Digital Twin technologies through cloud-edge architectures, enabling real-time diagnostics, predictive maintenance, and enhanced battery lifetime management. Their findings suggest that future BMS solutions will increasingly rely on combining physical battery models with AI-driven analytics to achieve reliable long-term operation of autonomous renewable-energy-powered systems.

3. Methodology

To rigorously compare the SoC estimation approaches under realistic marine conditions, a comprehensive simulation framework was developed using MATLAB R2023b. The methodology includes scenario-based data generation, realistic sensor noise modelling, and the implementation of both the CC and DL estimation approaches. The simulation environment represents a typical Mediterranean summer day, characterised by extended daylight hours and elevated ambient temperatures, reflecting realistic operating conditions for coastal smart buoy systems. The overall experimental workflow is illustrated in Figure 1.

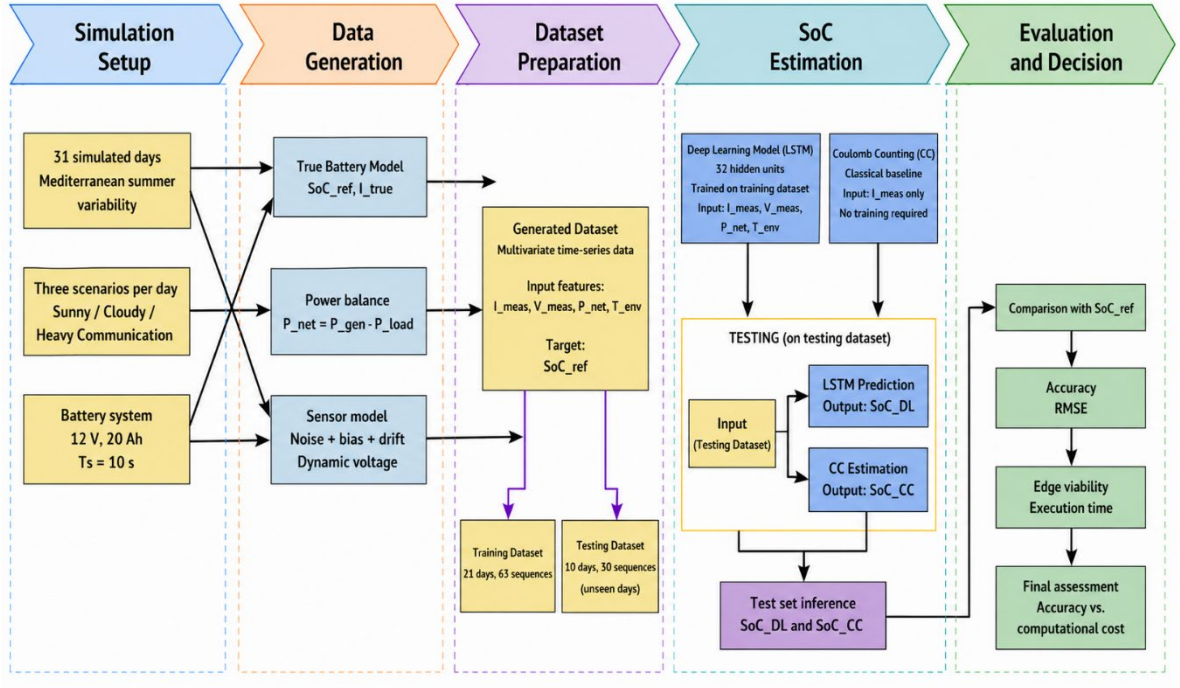


Figure 1. Flowchart of the proposed methodology comparing CC and DL SoC estimation under simulated marine conditions

3.1. Battery Parameters and Environmental Modelling

The simulated energy storage system is a 12 V, 20 Ah Li-ion battery, typical for automated smart buoy platforms (Bojic *et al.*, 2021). The simulation is performed over a 31-day period, where each day is represented as a 24-hour time series with a sampling interval of 10 seconds. Each day includes variations in environmental conditions reflecting realistic Mediterranean summer variability. To emulate realistic summer marine conditions characteristic of the Mediterranean climate, the environmental temperature profile is modelled as a sine wave. The simulation covers 15 hours of daylight (from 05:00 to 20:00). The temperature profile fluctuates between a warm nocturnal minimum of 22 °C and a diurnal peak of 42 °C. Notably, this peak represents the internal temperature within the buoy enclosure under direct solar irradiance, rather than the ambient sea surface temperature.

3.2. Operational Scenarios

For each simulated day, three operational scenarios were defined to capture different energy conditions. The power parameters were scaled to match the nominal battery capacity of 240 Wh for the selected battery system, using a maximum solar generation of 30 W and a base sensor load of 10 W:

- Scenario 1 (Sunny): High solar energy availability with a constant base load.
- Scenario 2 (Cloudy): A 50% reduction in solar generation due to simulated cloud cover, with a constant base load.
- Scenario 3 (Heavy Communication): High solar energy availability with aggressive load spikes. To simulate satellite or telemetry data transmissions, 15 W load spikes lasting 120 seconds were introduced every 30 minutes. The 15 W load spikes in high-bandwidth telemetry tasks, such as transmitting Automatic Identification System(AIS) data using !AIVDM sentences or exchanging raw radar video in the ASTERIX Category 240 format (Tsvetkov and Alexandrov, 2016).

Together, these scenarios assess smart buoy performance across a wide range of operational conditions and energy demands.

3.3. Sensor Noise and Parameter Corruption

To replicate the limitations of low-power edge hardware and cost-effective sensors typical in remote marine applications, the ideal outputs from the True Battery Model were corrupted using a stochastic noise layer. A Gaussian white noise model was applied to voltage measurements. Simultaneously, the current readings were subjected to both random noise and a constant bias to simulate cumulative sensor drift, a significant challenge in marine energy storage monitoring (Fu *et al.*, 2022). This persistent drift represents the most critical failure point for traditional integration-based estimation methods, as measurement errors continuously accumulate over time, leading to significant SoC divergence (Zhang *et al.*, 2022).

3.4. Reference SoC

The reference SoC was calculated using the ideal battery current derived from the net power balance:

$$P_{net} = P_{gen} - P_{load} \tag{1}$$

The corresponding battery current was then calculated as:

$$I_{true} = \frac{P_{net}}{V_{bat}} \tag{2}$$

where V_{bat} is the battery voltage.

The SoC was then determined by integrating the current over time, following the Coulomb counting principle:

$$\mathrm{SoC_k} = \mathrm{SoC_{k-1}} + \begin{cases} \dfrac{\eta_{\mathrm{ch}} \times \mathrm{I_k} \times \Delta \mathrm{t}}{\mathrm{Q}}, & \mathrm{I_k} \geq 0 \\ \dfrac{\mathrm{I_k} \times \Delta \mathrm{t}}{\eta_{\mathrm{dis}} \times \mathrm{Q}}, & \mathrm{I_k} < 0 \end{cases} \tag{3}$$

Where SoC_k is the state of charge at the current time step, $I_k$is the battery current, Δt(10s) is the sampling interval, Q is the nominal battery capacity, and $\eta_{ch}$and η_{dis} represent the charging and discharging efficiencies, respectively (Fu et al., 2022; Zhang et al., 2022). This reference SoC represents the ground truth and was used both as the training target for the DL model and as the benchmark for evaluating estimation accuracy.

3.5. State of Charge Estimation Algorithms

To provide a comprehensive analysis of SoC estimation under marine conditions, two approaches were implemented and compared: a classical integration-based method and a data-driven DL model. to handle non-linear environmental disturbances. Both algorithms use a simulated dataset incorporating measurement noise, bias, and drift. The dataset consists of multivariate time-series data including measured current, voltage, net power, and environmental temperature, with the reference SoC as the target variable.

3.5.1. Dataset Structure and Train-Test Split

The generated dataset consists of 31 simulated days, with each day including three operational scenarios (sunny, cloudy, and heavy communication), resulting in a total of 93 time-series sequences. The dataset was

divided into training and testing subsets based on full-day separation. The training set consists of 21 days (63 sequences), while the remaining 10 days (30 sequences) were used for testing.

This approach ensures that the model is evaluated on previously unseen days, allowing for a realistic assessment of generalisation performance under varying environmental conditions.

3.5.2. Classical Approach

The classical Ampere-hour integration (CC) method was implemented as the baseline approach. In its discrete form, as implemented in the simulation, the SoC at step k is calculated as described by two group of authors (Zhang *et al.*, 2022; Madani *et al.*, 2025)

$$SoC_k = SoC_{k-1} + \frac{I_k \times \eta \times T_s}{Q_C} \tag{4}$$

where I_k is the current measured by the sensor (which contains bias and drift), T_s is the sampling interval (10 s), and Q_C is the nominal battery capacity (72,000 Coulombs). To ensure consistency with the reference model, η represents the Coulombic efficiency, set to 0.95 for both charging and discharging phases. This approach was implemented using vectorised array operations to maximise computational efficiency during evaluation.

3.5.3. DL Approach

To counter the cumulative drift and non-linearities inherent in the classical method, a Long Short-Term Memory (LSTM) neural network was designed. The network input at each time step is defined as $x_k = [I_{meas,k}, V_{meas,k}, P_{net,k}, T_{env,k}]^T$, forming a multivariate time-series sequence. To ensure training stability and convergence, min-max normalization was applied to all features using the MATLAB mapminmax function. The architecture comprises a sequence input layer, an LSTM layer with 32 hidden units to capture temporal dependencies in the battery data, a fully connected layer, and a final regression layer. The model was trained using the Adam optimiser for 150 epochs with a mini-batch size of 1. This data-driven approach enables the network to implicitly learn the complex relationships between temperature fluctuations ($T_{env,k}$), voltage drops, and the actual SoC, eliminating the need for manual parameter tuning (Zhang et al., 2022).

3.6. Performance Evaluation and Analysis

Following the SoC estimation phase, an automated framework was developed to assess the viability of each approach for smart buoy deployment. Performance was analysed based on two primary criteria, accuracy and edge viability.

The estimation error was quantified using the Root Mean Square Error (RMSE) (Zhang *et al.*, 2022). The RMSE is calculated as

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}\left(SoC_{ref,k} - SoC_{est,k}\right)^2} \tag{5}$$

where N represents the total number of simulation samples, $SoC_{ref,k}$ is the ground truth value at the time step k and $SoC_{est,k}$ is the value predicted either by CC or DL method.

To evaluate suitability for low-power edge hardware, the computational cost was assessed by measuring the direct execution time (in seconds) for each algorithm during the inference phase. As shown in Section 3 of the methodology flowchart in Figure 1, this dual-metric analysis leads to a final assessment of the recommended approach for autonomous marine monitoring systems.

4. Results and Discussion

This section provides a detailed evaluation of the simulated data, focusing on the comparative performance of the CC and DL algorithms under varying marine conditions. The analysis moves from the experimental setup to the interpretation of accuracy metrics and computational efficiency, based on a month-long simulation with

stochastic environmental variations. The visual results of the simulation are shown in Figures 2, 3, and 4. In all scenarios, the reference SoC (SoC_{ref}, represented by the blue line) serves as the benchmark. Figure 2 presents the results for Scenario 1 (Sunny day). Under favourable solar conditions, the battery undergoes a pronounced charging phase, reaching full saturation (100% SoC) around midday. The Coulomb Counting (CC) method (red line) shows a clear upward drift, caused by the accumulation of sensor bias and current drift over time. This results in premature saturation and a systematic overestimation of the SoC. In contrast, the LSTM-based estimate (yellow line), although slightly affected by measurement noise, closely follows the reference trajectory throughout the entire cycle. The model successfully compensates for both stochastic noise and systematic bias, demonstrating strong robustness.

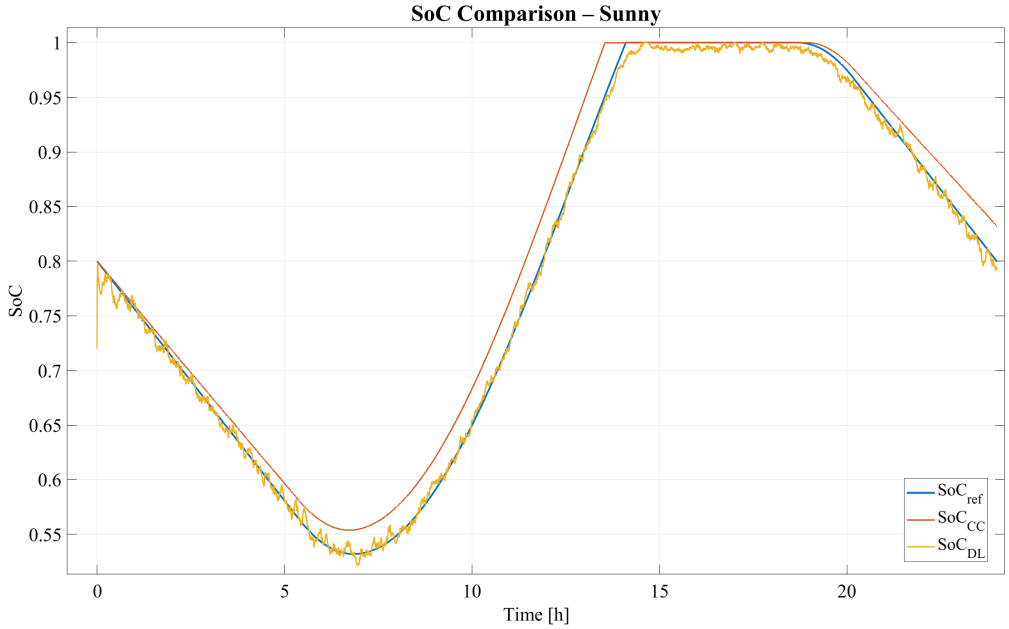


Figure 2.Scenario 1- Sunny day

Figure 3 presents Scenario 2 (Cloudy day), which represents the most challenging operating condition due to reduced solar generation and extended discharge periods. In this case, the CC method shows a significant and continuous divergence from the reference SoC, resulting in the largest observed estimation error. This behaviour confirms that integration-based methods are highly sensitive to cumulative errors, particularly in low-generation scenarios. Conversely, the LSTM model maintains high fidelity to the reference profile, effectively correcting drift by leveraging additional input features such as voltage and temperature.

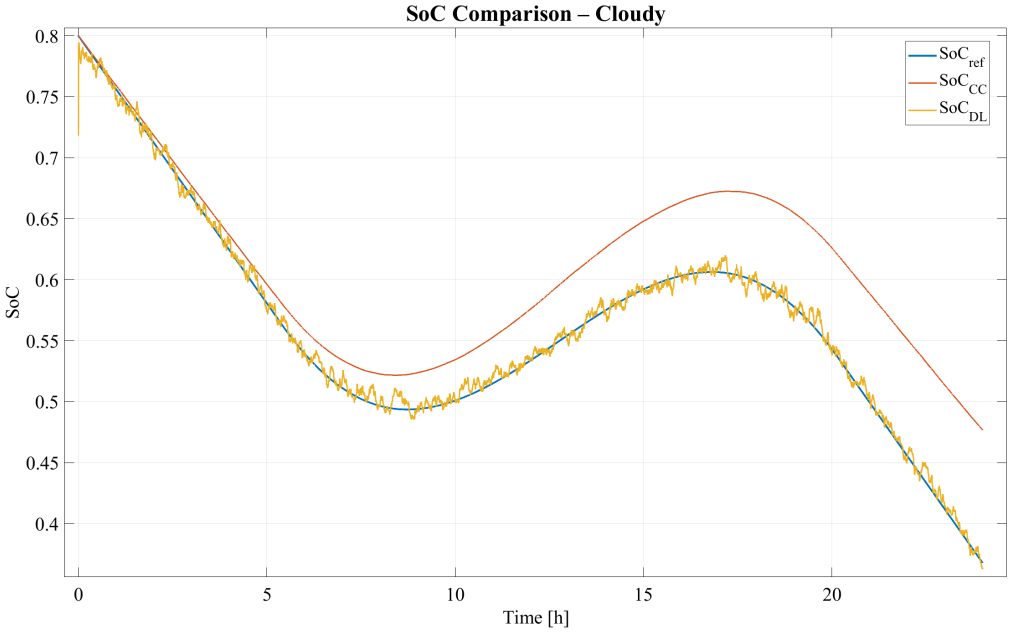


Figure 3. Scenario 2- Cloudy day

Finally, Figure 4 shows Scenario 3 (Heavy Communication). The introduction of random communication spikes causes rapid fluctuations in load and current. While these disturbances introduce visible high-frequency variations in the LSTM output, the overall SoC trajectory remains accurately captured. The CC method again reaches saturation prematurely and remains overestimated during the peak charging period, resulting in noticeable deviation from the reference.

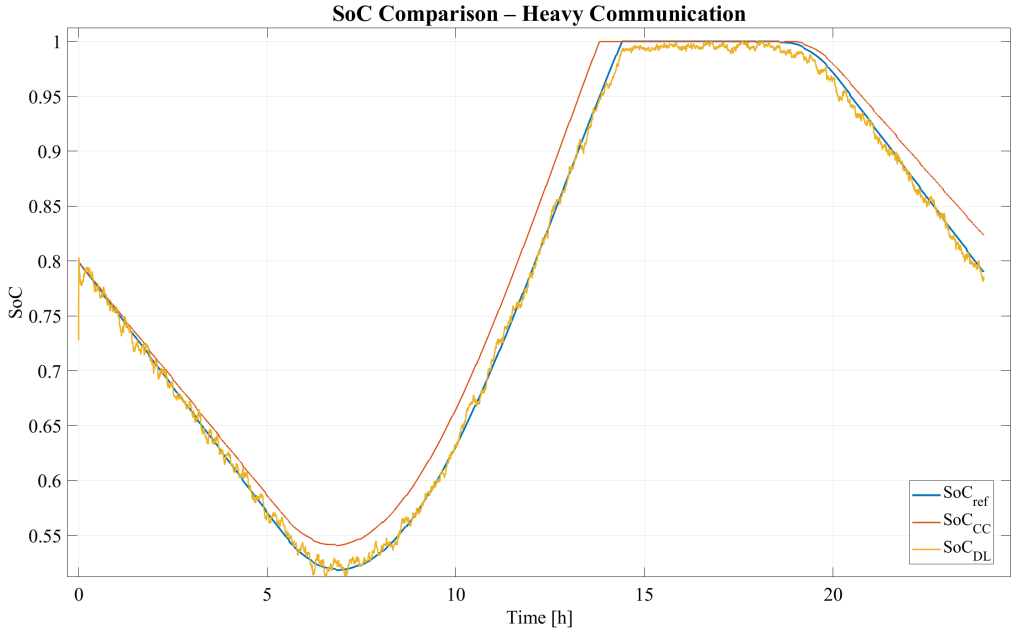


Figure 4. Scenario 3- Heavy Communication

4.1. Quantitative Metric Evaluation

The simulation's statistical findings, quantifying accuracy via RMSE and computational cost via algorithmic execution time, are summarized in Table 1.

Table 1.Summary of SoC Estimation Results and Computational Efficiency across Scenarios

Scenario_ID	Scenario	RMSE_CC	RMSE_DL	Time_CC(s)	Time_DL(s)
1	Sunny	0.023681	0.0057092	0.00010048	0.039864
2	Cloudy	0.055835	0.0054938	0.00011217	0.018996
3	Heavy Communication	0..032101	0.0059823	0.00008712	0.018557

4.2. Discussion

The numerical results confirm that the LSTM-based DL approach consistently outperforms the CC method in all three scenarios. The most notable improvement occurs in the Cloudy scenario, where the RMSE decreases from 0.055835 for CC to 0.0054938 for the LSTM model. This represents approximately a tenfold reduction in estimation error, clearly demonstrating the DL approach's ability to compensate for accumulated sensor errors under reduced solar generation. A similar pattern is seen in the Sunny scenario, where the LSTM reduces the RMSE from 0.023681 to 0.0057092, and in the Heavy Communication scenario, where the error decreases from 0.032101 to 0.0059823. On average, the DL model achieves an RMSE of approximately 0.00573 across all scenarios, compared with approximately 0.03721 for the CC method. This corresponds to an average error reduction of about 84.6%. From a computational perspective, the CC method remains significantly faster, with execution times on the order of seconds. However, the LSTM inference time remains below 0.04 s in all scenarios. Since the sampling interval of the simulated smart buoy system is 10 s, the maximum LSTM execution time represents less than 0.4% of the available processing interval. Therefore, despite the higher computational demand compared with CC, the DL approach remains feasible for real-time SoC estimation in the simulated edge-monitoring context.

5. Conclusion

This study systematically evaluates the trade-offs between traditional integration-based SoC estimation methods and modern DL approaches in the context of autonomous smart buoy systems. A simulation framework was developed using MATLAB computing platform to reflect realistic Mediterranean marine operating conditions, including variable solar generation, stochastic load profiles, and temperature variations, allowing for clear identification of the limitations and advantages of each approach. The results show that the classical CC method, although computationally efficient and easy to implement, is inherently sensitive to sensor inaccuracies. In particular, current bias and drift cause cumulative integration errors, resulting in significant deviation from the reference SoC over time. This limitation was most evident in the Cloudy scenario, where the CC method produced an RMSE of 0.055835, while the LSTM-based DL model reduced the error to 0.0054938. This represents an approximately tenfold reduction in estimation error and clearly demonstrates the improved robustness of the data-driven approach. Additionally, the method does not inherently account for nonlinear battery behaviour or temperature-dependent effects, reducing its reliability under realistic environmental conditions. In contrast, the LSTM-based DL model demonstrated strong robustness across all tested scenarios. The model effectively learned the underlying relationships between measured current, voltage, power balance, and environmental temperature, enabling it to compensate for measurement noise, drift, and nonlinear system dynamics. Consequently, it consistently achieved high accuracy, maintaining RMSE values below 0.011 even under challenging conditions such as reduced solar input and aggressive load fluctuations. From a computational perspective, the analysis confirms the expected trade-off between accuracy and complexity. Although the DL model requires more execution time than CC method, the observed computational overhead remains within acceptable limits for typical marine telemetry systems, where sampling intervals are on the order of seconds. The maximum LSTM inference time was 0.039864 s, which is less than 0.4% of the 10 s sampling interval used in the simulation. This suggests that deploying lightweight DL models on edge devices is feasible, provided that appropriate hardware and optimisation strategies are considered.

Overall, the findings indicate that moving from deterministic, physics-based methods to data-driven approaches can significantly improve the reliability and resilience of smart buoy energy management systems, particularly under complex and uncertain operating conditions. Future work should focus on implementing the proposed DL model on embedded edge hardware and extending it with additional battery health indicators to further enhance system performance and the operational lifetime of autonomous marine sensing networks.

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A Comparative Performance Analysis of Nuclear Marine Propulsion Plants using Supercritical CO_2 and Conventional Steam Cycles

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Abstract:

Nuclear marine propulsion systems have traditionally relied on the superheated steam Rankine cycle, which, despite its maturity, presents limitations in terms of efficiency, size and system complexity. This study provides a comparative thermodynamic and dimensional analysis between a conventional steam Rankine cycle and a supercritical CO_2 Brayton (sCO_2) recompression cycle for application in future nuclear-powered vessels. Both thermodynamic cycles are modelled at nominal steady state conditions and the dimensional study is performed within a common boundary that excludes the heat sources. The LNG carrier Cadiz Knutsen, with 28 MW of installed propulsion power, is used as case study vessel. Under the selected sCO_2 operating conditions, the recompression cycle produces 28.70 MW of gross turbine power and 15.51 MW of net cycle power after main compressor and recompressor consumption. The resulting net thermal efficiency is 38.42%, corresponding to an absolute gain of 6.20% points relative to the conventional steam Rankine cycle. In addition, the high density of supercritical CO_2 enables a substantial reduction in turbomachinery size and overall footprint in the engine room. The findings indicate that sCO_2 technology offers significant advantages in terms of power density and spatial integration for future nuclear propulsion systems. However, significant challenges related to compact heat exchanger design and material selection remain.

Keywords: Nuclear marine propulsion; Supercritical CO_2 Brayton cycle; Steam Rankine cycle; Energy efficiency; Power density.

1. Introduction

The global objective of decarbonizing power generation in maritime transport requires a fundamental re-evaluation of marine propulsion systems (Díaz-Secades, González and Rivera, 2023). The International Maritime Organization has introduced stringent Carbon Intensity Indicator (CII) regulations, placing significant regulatory pressure on existing merchant fleets (González Gutiérrez *et al.*, 2023). While alternative high energy density sources are being explored, the efficiency of converting thermal energy into propulsion power remains a major key engineering challenge. For decades, the conventional steam Rankine cycle, commonly implemented in Dual Fuel Steam Turbine Mechanical plants, has been the industry standard particularly for LNG carriers (Meana-Fernández *et al.*, 2020). However, its application is greatly limited by the large size of its boilers, turbines, main condenser and heat exchangers, which restricts the vessel available cargo capacity. In contrast, power cycles based on supercritical carbon dioxide (sCO_2) have attracted significant scientific attention in recent years, since when operating above its critical point (31.1°C and 73.8 bar), sCO_2 exhibits a unique combination of thermophysical properties, including liquid-like density and gas-like viscosity (Zhu *et al.*, 2020). These characteristics enable reduced compression work and highly compact turbomachinery.

The objective of this study is to provide a comparison between conventional steam Rankine cycle and supercritical CO_2 Brayton cycle, addressing the current gap in the literature regarding their techno-economic integration in marine propulsion systems, especially for application in future nuclear-powered vessels.

2. The Conventional Steam Rankine Cycle Baseline: Cadiz Knutsen tanker case study

To ensure a realistic comparative analysis, the 77,237-ton LNG tanker Cádiz Knutsen was selected as the baseline vessel, based on data from NuProShip I project report, which focuses on the application of nuclear technology to marine propulsion (Emblemsvåg *et al.*, 2025). The vessel operates with a conventional



« Cadiz Knutsen »

Main Dimensions		**Cargo arrangement**	
Vessel type	LNG Carrier	Four (4) cargo tanks, total capacity 138 000 m³	
Length overall	284.40 m		
Length between perp.	271.00 m	**Propulsion**	
Breadth	42.50 m	Type	Steam driven turbine
Depth to main deck	25.40 m	Power	28 000 kW
Scantling draught	12.30 m	Revolutions	83 rpm
Design draught	11.40 m		
Deadweight (design)	68 200 tns	**Main Boilers**	
Gross Tonnage	93 450 GT	2 x MHI boilers	65 000 kg/h
Service Speed	19.5 knots	Steam condition	61.8 kg/cm² x 515 °C

regenerative steam Rankine cycle, requiring a continuous shaft power output of 28,000 kW (Figure 1).

Figure 1. LNG carrier Cadiz Knutsen (Emblemsvåg et al., 2025)

The steam Rankine cycle was modelled based on the Cadiz Knutsen heat balance documentation and machinery information. The main propulsion system consists of dual fuel boilers supplying superheated steam at 63.60 bar and 515 °C to the main propulsion turbines. The heat balance uses three steam and water flow rates that correspond to different locations - the boiler feedwater flow rate, the superheated steam flow available at the boiler outlet and the main turbine inlet flow which depends on the branch flows and extractions for auxiliary services and feedwater heating. Figure 2 depicts the simplified steam power plant scheme of the vessel.

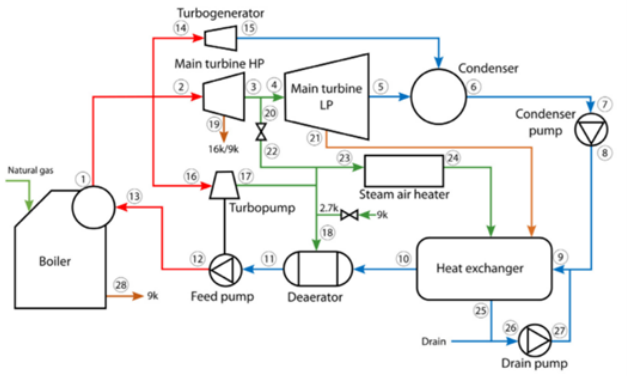


Figure 2. Vessel simplified steam power plant scheme

The total thermal power supplied by the boilers to the cycle ($\dot{P}_{boiler}$) is determined from the energy balance between the feedwater entering the boiler and the generated superheated steam, including the small auxiliary and extraction terms reported in the heat balance, as represented in Eq. 1:

$$\dot{P}_{boiler} = \dot{m}_{steam\ out} \cdot h_{steam\ out} + \dot{m}_{des.\ out} \cdot h_{des.\ out} - \dot{m}_{water\ in} \cdot h_{water\ in} \quad (1)$$

The main thermodynamic properties of the steam cycle, obtained from the vessel heat balance diagrams, are summarized in Table 1.

Table 1. Steam cycle thermodynamic values

Thermodynamic parameter	Value	Unit
Superheated steam temperature at boiler outlet	515.00	°C
Boiler outlet superheated steam enthalpy ($h_{steam\ out}$)	3,453.47	kJ/kg
Steam enthalpy at turbine first stage inlet	3,443.85	
Extracted desuperheated steam enthalpy ($h_{des.\ out}$)	2,807.46	
Feedwater enthalpy ($\dot{m}_{water\ in}$)	591.62	
Main turbine inlet steam flow rate	24.25	kg/s
Boiler feedwater flow rate ($\dot{m}_{water\ in}$)	27.40	
Desuperheated extraction steam flow rate ($\dot{m}_{des.\ out}$)	0.25	
Boiler outlet superheated steam flow rate ($\dot{m}_{steam\ out}$)	27.15	

It was estimated that the boilers supply a total thermal input power of 78,253.19 kW to the cycle. This value corresponds to the boiler side thermal input and should not be confused with the lower main turbine inlet flow after auxiliary branches and steam extractions. The high pressure and low pressure turbine stages, including steam extractions for feedwater preheating and auxiliary services, generate the mechanical power output (Fernández *et al.*, 2017). Considering a reduction gear efficiency of 99% and a shaft line efficiency of 99%, the net shaft power is estimated at 24,959.79 kW at 90% Maximum Continuous Rating, which is in close agreement with the reported value of 25,200 kW in the vessel heat balance diagrams. The thermal efficiency of the Rankine cycle is given by the ratio between the total thermal power and the thermal power supplied by the boilers. This results in a thermal efficiency of 32.22%. Although historically acceptable, this relatively low efficiency poses significant challenges under current environmental regulations, making steam-powered vessels particularly vulnerable to CII non-compliance.

3. The Supercritical CO_2 Brayton Cycle Arrangement

A recompression sCO_2 Brayton cycle was evaluated at nominal operating conditions representative of advanced reactor coupling. The case was not scaled to deliver the same 28 MW shaft power as the reference vessel. Instead, the comparison uses the same efficiency definition, a common power cycle boundary, and a subsequent discussion of size and cost implications.

3.1 Mitigation of the Pinch Point via Recompression

A simple closed-loop sCO_2 Brayton cycle consists of a compressor, a heat source, a turbine and a recuperator. However, near the pseudo-critical region, sCO_2 exhibits a sharp non-linear variation in specific heat capacity (Wang *et al.*, 2023). As a result, the fluid exiting the main compressor has a significantly higher heat capacity than that exiting the turbine, requiring more energy to increase its temperature. This imbalance causes the temperature profiles of the hot and cold streams within the recuperator to converge prematurely, leading to the so-called “pinch point”, which limits heat transfer effectiveness (Lee *et al.*, 2023). To overcome this limitation, a recompression cycle configuration was adopted. By splitting the mass flow rate upstream of the pre-cooler and introducing a secondary compressor (recompressor, RC), the mass flow rate on the cold side of the Low-Temperature Recuperator (LTR) is reduced. This approach balances the thermal capacity rates, mitigates the pinch point and enhances internal heat recuperation (Dostal *et al.*, 2002).

3.2 Boundary Conditions and Thermodynamic Model

To design and evaluate the sCO_2 cycle integrated with a nuclear heat source, the reactor was represented as an external thermal boundary condition rather than as a stand-alone neutronic or thermal hydraulic reactor model. Consequently, no reactor core simulation was performed in this work. The thermal coupling is defined through the intermediate heat exchanger (IHX), which transfers heat from the reactor side to the closed sCO_2 loop.

According to Xu, 2017, a turbine inlet temperature (TIT) of 600 °C is achievable considering a core outlet temperature of 700 °C in a Molten Salt Reactor (MSR). Ahn and Lee, 2014 state that the optimal range of TIT for this class of power cycles lies between 550 °C and 700 °C. Consolidating these specifications and building upon the reference cycles developed by various authors (Lee *et al.*, 2023; Molière *et al.*, 2024), the baseline boundary conditions were established, with the respective operational parameters summarized in Table 2.

Table 2. Boundary Conditions and equipment efficiencies for the Recompression Cycle.

Boundary Conditions for the Recompression sCO_2 Cycle	Values	Unit
Cycle maximum pressure	22.50	MPa
Cycle minimum pressure	7.50	
Cycle maximum temperature	550.00	°C
Cycle minimum temperature	45.00	
Cycle total flowrate	702.00	t/h
Turbine isentropic efficiency	93.00	%
Compressor isentropic efficiency	85.00	
Heat exchangers efficiency	95.00	
Flowrate fraction to recompressor	24.00	

Based on (Molière *et al.)*, 2024, the optimal recompression fraction was set at 24%. Figure 3 illustrates the sCO_2 recompression cycle modelled and its thermal coupling with the reactor IHX.

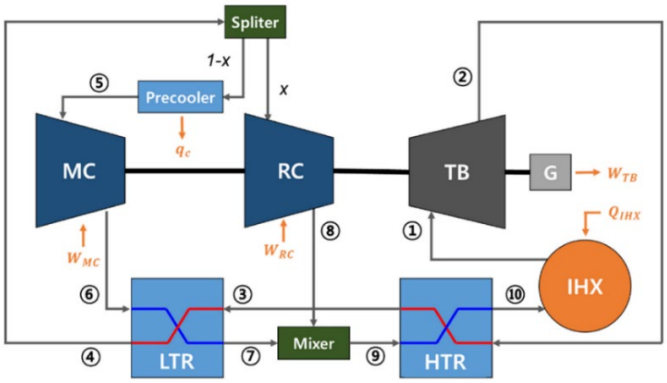


Figure 3. Recompression Cycle of sCO_2 (Lee *et al.*, 2023)

The thermal efficiency η_T of the recompression cycle is defined by the net power over the thermal input from the reactor's intermediate heat exchanger (IHX), Eq. 2:

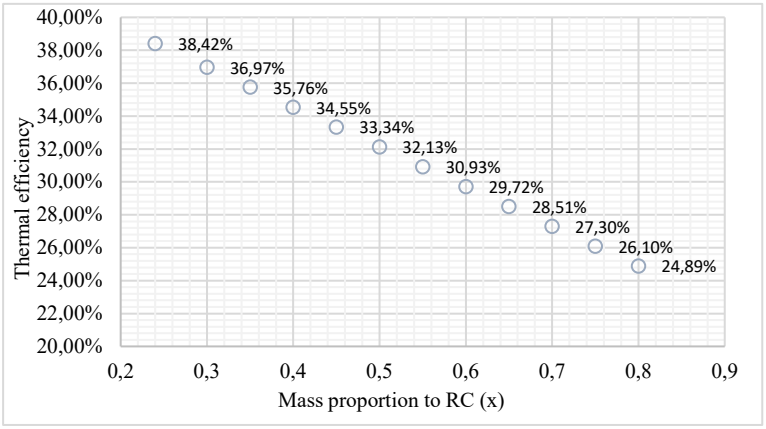
$$\eta_T = \frac{\dot{P}_{turbine} - (\dot{P}_{MC} + \dot{P}_{RC})}{\dot{Q}_{reactor}} \tag{2}$$

where $\dot{P}_{turbine}$ is the turbine power output, $\dot{P}_{MC}$ and $\dot{P}_{RC}$ are the power consumptions of the main compressor and recompressor, respectively, and $\dot{Q}_{reactor}$ is the thermal input from the reactor. Additionally, to calculate the compressor power consumption, for example, the Eq. 3 was applied:

$$\dot{P}_{main\ compressor} = (1 - x) \cdot \dot{m}_{total} \cdot (h_6 - h_5) \tag{3}$$

The enthalpies across every cycle stage were calculated from the CO_2 thermodynamic properties at each temperature and pressure. The compressor power consumptions are 8.25 MW for the main compressor and 4.94 MW for the recompressor. The expansion of 195 kg/s (702 t/h) of sCO_2 from 22.50 MPa to 7.50 MPa gives a gross turbine power of 28.70 MW, with a reactor heat input of approximately 40.37 MWth at the IHX After subtracting both compression loads, the net cycle power is 15.51 MW. Under these conditions, the sCO_2

recompression cycle achieves an overall net thermal efficiency of 38.42%, representing an absolute increase of 6.20 % points compared with the conventional steam Rankine cycle. It was verified that the thermal efficiency depends on mass flow rate of the recompressor. Figure 4 shows the sensitivity of the thermal efficiency with the mass flow rate fraction through the recompressor. The maximum efficiency, in the analyzed range occurs



at the selected recompression fraction of 24%. As the recompression fraction increases, the recompressor power demand rises and the net efficiency decreases, reaching values close to the Rankine baseline around $x = 0.50$ and falling to 24.89% at $x = 0.80$. This parametric sweep confirms that the flow split is a critical design variable for both thermodynamic performance and component sizing.

Figure 4. Thermal efficiency versus mass flow rate proportion through the recompression compressor

The present study therefore reports a focused parametric analysis of the recompression fraction while maintaining the pressure ratio, turbine inlet temperature and component efficiencies fixed at the baseline values reported in Table 2. A broader multi parameter optimization, including pressure level, TIT, recuperator effectiveness and cooling temperature, is recommended as future work because those variables depend strongly on the detailed reactor, IHX and marine cooling system design.

4. Dimensional Analysis

The thermodynamic balance shows that the selected sCO_2 case produces 15.51 MW of net cycle power and reaches a net thermal efficiency of 38.42%. The sensitivity analysis in Figure 4 shows that the recompression fraction strongly affects the result and must be carefully selected during cycle design. Beyond thermodynamic performance, a key advantage of sCO_2 technology in maritime applications lies in its impact on Size, Weight and Power (SWaP) metrics. These aspects are particularly relevant in ship design, where machinery footprint directly affects cargo capacity and vessel integration. The main dimensional benefits are discussed in the following subsections.

4.1 Turbomachinery

Based on different studies it was verified that the cross-sectional area of turbomachinery is inversely proportional to the working fluid density. Therefore, the near-liquid density of sCO_2 enables a significant reduction in component size compared to conventional steam propulsion systems.

- Compressors: De Villiers *et al.*, 2025, indicate that a radial, multi-stage sCO_2 compressor operating at a mass flow rate of 195 kg/s can achieve impeller diameters below 400 mm, allowing efficient use of available space.
- Turbine: Li *et al.*, 2022 indicate that a representative 25 MW, four-stage sCO_2 turbine has a maximum diameter of approximately 0.26 m, a total length of 2.54 m, and a weight of around 850 kg. In contrast, an equivalent 30 MW marine steam turbine occupies a significantly larger volume, with a typical weight of approximately 305 tons and dimensions spanning several meters.

4.2 Printed Circuit Heat Exchangers

In the sCO_2 cycle, the large steam condenser and other heat exchangers of the Rankine steam system are replaced by compact Printed Circuit Heat Exchangers (PCHEs), which act as the high-temperature (HTR) and low-temperature (LTR) recuperators. These devices operate using micro-channel heat transfer, enabling very high heat transfer coefficients and compact designs. PCHE units may occupy a total volume of approximately 8.5 m³ (Cha *et al.*, 2009), making them well suited for integration within constrained marine engine room arrangements. Table 4 shows a summary about the general dimensions of the equipment described.

Table 3. General dimensions of the equipment for both cycles.

Component	sCO_2 cycle	Rankine cycle
Heat source	TMSR-LF reactor is approximately 12.20 m tall (Ocean-Power and Copenhagen Atomics to explore thorium-based energy in Norway)	Marine boiler with a 55,000 kg/h steam production capacity most common model is 8.9×4.23×5.21 m (KangRim MD07 Boiler Specifications | KangRim Boilers)
Turbine	Total length of 2.54 m, maximum diameter of 0.26 m and total weight of 850 kg for 25 MW (Li et al., 2022)	Minimum length of 5.1 m and variable diameter (Stepanek, Syblik and Entler, 2022)
Heat exchangers	A volume of between 1.15 and 8.50 m³ for power outputs of 1 MW and 50 MW respectively (Pandey, Kumar and Dutta, 2024)	For a marine steam propulsion plant, the volume occupied is between 80 and 100 m^3 (Kwon *et al.*, 2020)

5. Technoeconomic Analysis

To evaluate the commercial viability of the proposed system at screening level, a technoeconomic analysis was performed based on established cost estimation methodologies. The scope includes the sCO_2 turbine, main compressor, recompressor, PCHE recuperators and an indicative 100 MWth reactor module cost. It excludes hull modifications, nuclear licensing, shielding, safeguards, port infrastructure, crew training, financing, downtime and decommissioning. Therefore, the results should be interpreted as order of magnitude CAPEX estimates rather than as a complete lifecycle cost assessment. The approach initially followed the correlations proposed by (Turton *et al.*, 2008), adapted to account for sCO_2 turbomachinery characteristics. However, these correlations do not fully cover the power range of the components considered in this study. Therefore, alternative cost correlations from (Weiland, Lance and Pidaparti, 2019) were also considered, despite their higher associated uncertainty. All cost estimates were updated using the Chemical Engineering Plant Cost Index (CEPCI) reported in (Díaz-Secades *et al.*, 2026). The capital cost correlations are primarily based on component power, maximum operating temperature and pressure level. For the turbine, the cost is estimated from the power variable used in the original turbine correlation and a temperature correction factor, Eq. 4:

$$C_{turbine} = 182{,}600 \cdot \dot{P}_{shaft}^{0.5561} \cdot f_{turbine} \tag{4}$$

where $f_{turbine}$ is the temperature correction factor based on the maximum temperature reached in the cycle. Weiland, Lance and Pidaparti (2019) report an absolute error of approximately ±19.00% for the axial turbine correlation. The compressor cost is estimated from the individual compressor power, Eq. 5:

$$C_{compressor} = 1{,}230{,}000 \cdot \dot{P}_{shaft}^{0.3992} \tag{5}$$

For the multistage compressor correlation, the reported error is approximately ±31.50%. PCHE costs and volumes were taken from literature ranges for sCO_2 recuperators and scaled to the present power level. The reactor cost was introduced as an indicative value for a 100 MWth class MSR module and is included only to represent the expected order of magnitude of the investment. Based on these assumptions, the Capital Expenditure (CAPEX) breakdown of the propulsion system is summarized in Table 5:

Table 4. CAPEX breakdown of the sCO_2 propulsion system.

Machinery components	Cost (Euro)
Main compressor	3,228,320

Recompressor	2,631,980
sCO_2 Turbine	1,335,050
PCHE recuperators (HTR & LTR)	36,665
Nuclear reactor (100 MWt, e.g. Copenhagen Atomics TMSR)	43,000,000
Total estimated CAPEX	50,232,015

The total estimated CAPEX of the nuclear sCO_2 propulsion module is approximately 50.23 million Euro (approximately USD 58.41 million). These values are estimates and should be interpreted within the uncertainty of the correlations. Since this work does not include fuel cost, lifecycle cost, nuclear licensing cost or a quantified economic offset from additional cargo capacity, the economic conclusion is limited to CAPEX order of magnitude and potential spatial benefits. Statements regarding lower operating cost or lifecycle advantages were therefore moderated, and a dedicated lifecycle economic assessment is identified as future work.

6. Conclusion

This study presented a comparative analysis between conventional steam Rankine and supercritical CO_2 Brayton cycles for marine propulsion applications. The results indicate that the selected sCO_2 recompression cycle, when coupled through an IHX to a molten salt reactor heat source, can achieve a net thermal efficiency of 38.42%. This corresponds to an absolute improvement of 6.20 percentage points over the baseline system based on the Cadiz Knutsen LNG carrier. The sCO_2 base case produces 28.70 MW of gross turbine power and 15.51 MW of net cycle power after compression loads, so the comparison is not a power equivalent replacement of the 28 MW vessel shaft requirement at the reported mass flow rate. In addition to thermodynamic performance, the high density of supercritical CO_2 enables a significant reduction in turbomachinery size, potentially up to an order of magnitude smaller than conventional steam systems. This reduction offers advantages in machinery footprint and vessel design flexibility, although the economic value of additional cargo capacity has not been quantified in this study. However, several challenges remain, particularly in the development of compact and cost effective heat exchangers, reactor integration, marine certification, shielding, safety systems and the high initial capital investment associated with nuclear propulsion systems. In summary, the sCO_2 Brayton cycle represents a promising alternative for future merchant marine propulsion from a thermodynamic and spatial integration perspective. The results support continued investigation, but final conclusions on operational cost, lifecycle cost and commercial viability require a dedicated economic assessment supported by reactor specific design data and marine regulatory assumptions.

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Development and Evaluation of a Digitalized Instruction Software for Collision Regulation Rules 13–18

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Abstract: This study aimed to develop a digitalized steering and sailing instructional software designed to enhance maritime students' understanding in applying Collision Regulation (COLREGs) Rules 13 to 18 within a classroom environment. Guided by the ADDIE Model, the study identifies students' learning difficulties in understanding overtaking, head-on, crossing situations, and responsibilities between vessels, which establish the need for an accessible, simulation-based learning tool that does not rely on full-mission bridge simulators. In the Design and Development Stages, the software prototype was built using Unity, C#, and JSON, integrating realistic navigational scenarios, maneuvering controls, environmental elements, feedback prompts, and interactive features to support experiential and constructivist learning. Implementation with 37 maritime students generated qualitative feedback highlighting key areas for refinement, including speed adjustments, improved realism, enhanced interactivity, personalized feedback, and interface usability. During the Evaluation Stage, 37 students and three experts assessed the software's usability, functionality, reliability, and performance, yielding high to very high acceptability ratings. Findings indicate that the software effectively simulates real-world collision-avoidance situations, improves learners' situational awareness, and strengthens their decision-making skills in applying COLREGs Rules 13–18. Overall, the digitalized instruction developed in this study demonstrates strong potential as an efficient, and practical supplementary tool for maritime education.

Keywords: Collision Regulation; Digitalized Instruction; software development, maritime education, simulation-based learning

1. Introduction

The majority of maritime incidents result from human factors (International Maritime Organization, 2023). In numerous instances, the level of watchkeeping was inadequate, or the watchkeeper lacked the necessary skills (MAIB, 2004). Anyone responsible for a vessel is obligated to accurately apply the Collision Regulation in every situation to ensure their own safety and the safety of other vessels navigating the seaway. When the master is not present on the bridge, the officer in charge of the navigational watch assumes responsibility for the safe navigation of the vessel, including compliance with COLREGs, while the master retains overall command of the ship (International Maritime Organization, 2017). COLREGs apply to all vessels upon high seas and in all waters connected therewith navigable by seagoing vessels (IMO, 2024). They are designed to prevent maritime collisions by establishing internationally recognized rules that promote the safe navigation of vessels at sea. Compliance with these rules reduces the risk of collision and enhances maritime safety. (Deckee, 2024). In addition to COLREGs, the IMO has also released a number of resolutions and codes concerning the enforcement of COLREGs. Moreover, numerous institutions offer thorough and comprehensive training and educational programs for the proper implementation of COLREGs (Demirel & Bayer, 2015). Numerous accidents that occurred in recent times resulting in hundreds of deaths have highlighted the human element, the importance of training, the function of the incident commander, making decisions under pressure and the environment in maritime safety (Havold, 2010). While numerous factors affect maritime safety, accident investigations have consistently identified human factors, including inadequate training, insufficient watchkeeping competence, and poor situational awareness, as major contributors to collision-related incidents. (Rothblum, 2000). Consequently, a successful Maritime Education and Training (MET) program is essential to enhance the quality of seafarers for the future. To further educate our students on COLREGs' steering and sailing rules inside the classroom without using a full-mission bridge simulator, the lead author, with the assistance of the co-authors, developed John B. Lacson Foundation Maritime University (Arevalo), Inc.'s very own digitalized instruction

software. The theoretical basis for developing this software is grounded in Experiential Learning Theory, which emphasizes learning through experience and reflection. Experiential learning emphasizes that the most effective method of learning is through direct experiences. The theory works in four stages- concrete learning, reflective observation, abstract conceptualization, and active experimentation (Western Governors University, 2020). By integrating interactive simulations that replicate real-world maritime scenarios, the software enables students to actively engage with and apply COLREGs in a controlled environment. This approach aligns with the Constructivist Paradigm, where learners construct knowledge through active participation and contextual application. Constructivism is a philosophical framework that ontologically highlights how a person actively builds their own understanding of reality through their thought processes (Lincoln and Guba, 2013). Furthermore, incorporating situational awareness and decision-making training within the software addresses critical understanding necessary for maritime safety, as highlighted in existing research. Using the ADDIE model, this study aimed to develop and evaluate our university's very own classroom-based, low-cost digital steering and sailing instructional software specifically designed for teaching COLREGs Rules 13-18. Unlike conventional full-mission bridge simulators, the software enables individualized, scenario-based maneuvering practice on standard computers, making simulation-assisted learning more accessible during regular classroom instruction.

Specifically, this study seeks answers to the following questions:

1. What are the perceived learning difficulties of maritime students in understanding and applying COLREGs Rules 13–18 that should inform the development of the instructional software?

2. What are the experts' perceptions of the acceptability and the students' perceptions of satisfaction with the developed steering and sailing instructional software in terms of usability, functionality, reliability, and performance?

3. What feedback and recommendations from students can be used to further improve the software prototype?

2. Methods

2.1 Research Design

This study employs a developmental research design, specifically a Type 2 product design and development approach following the ADDIE Model. Developmental research focuses on generating new knowledge through systematic design, development, and evaluation of products and models (Richey & Klein, 2013). The ADDIE Model- Analysis, Design, Development, Implementation, and Evaluation- provides a structured framework for comprehending user needs, prototyping, testing, and refining the software based on user feedback (Bouchrika, 2024). This approach is ideal for designing a computer-assisted steering and sailing software that allows students to experience vessel maneuvering inside the classroom without requiring a full-mission bridge simulator.

2.2 Respondents

This study involved several groups of respondents across different stages. During the Implementation Stage, one intact section composed of 37 students participated in the initial use of the software prototype. Another intact section of 37 students was involved in the Evaluation Stage to assess the software's performance and its impact on learning. Finally, in the Acceptability Stage, 1 COLREGs instructor, 1 deck officer, and one Information Technology (IT) specialist were engaged to evaluate the software's overall effectiveness, usability, and alignment with instructional and technical standards. The distribution of respondents is shown in Table 1.

Table 1. Distribution of Respondents

Category	f	%
Entire Group	37	100
A. 1 intact section (Implementation Stage)	37	100
B. 1 intact section (Evaluation Stage)	37	100
C. 1 COLREGs instructor; 1 deck officer; 1 IT specialist (Acceptability Stage)	3	100

2.3 Instruments

The study utilized two researcher-made instruments. The first was a Needs Assessment Questionnaire administered during the Analysis Stage. It consisted of learning objectives related to the application of COLREGs Rules 13–18, specifically overtaking situations (Rule 13), head-on situations (Rule 14), crossing situations (Rule 15), action by the give-way vessel (Rule 16), action by the stand-on vessel (Rule 17), and responsibilities between vessels (Rule 18). Students indicated the areas where they experienced learning difficulties, while an open-ended section allowed them to identify additional competencies that required instructional support. The second instrument was the Software Evaluation Questionnaire, which on the acceptability of three experts- an Information Technology (IT) specialist, deck officer, and a Collision Regulation instructor- consists of four dimensions: usability, functionality, reliability, and performance. Each dimension contained five items, resulting in a total of 20 statements. Example items included: "The software interface is easy to navigate" (usability); "The software performs the intended navigational simulations accurately" (functionality); "The software operates consistently without errors" (reliability); and "The software effectively improves my understanding of COLREGs Rules 13–18" (performance). A total of 20 questions needed to be responded using the 4-point Likert scale: strongly agree, agree, disagree, and strongly disagree. An open-ended question was also included to allow respondents to give their feedback or recommendations. In addition, the same questionnaire was answered by 37 students to determine their satisfaction level with the software prototype during the evaluation stage. The questionnaire underwent content validation by three experts: an Information Technology specialist, a maritime instructor, and a language editor. It was subsequently pilot-tested among 37 maritime students with characteristics similar to the target respondents. Internal consistency reliability was assessed using Cronbach's alpha, and the overall questionnaire yielded a coefficient of 0.91, indicating excellent internal consistency and demonstrating that the instrument was reliable for data collection.

2.4 Data Collection

The study follows the ADDIE model with data collection integrated into each stage. In the Analysis stage, researchers used a matrix for content analysis. This analysis was based on data gathered from a researcher-made survey questionnaire validated by three maritime instructors. The questionnaire was distributed to a purposively selected group of 37 students in an online version via Google Forms. During the Design stage, an IT expert developed simulation scenarios covering key Collision Regulation situations including overtaking, head-on situations, crossing scenarios, and responsibilities between vessels, with default course and speed settings established for simulated vessels. In the Development stage, a software prototype was programmed using Unity, C#, JSON, and incorporated interactive elements to replicate real-time ship maneuvering. The Implementation stage involved prototype testing by 37 students, each of whom has explored and used the software, with feedback collected via Google forms and integrated into further software improvements. The feedback collected from the implementation stage was looped back to the design stage, where it enhanced the software prototype. In the Evaluation stage, experts such as an IT specialist, deck officer, and Collision Regulation instructor assessed the software prototype using the Google forms questionnaire regarding the acceptability of the software in terms of usability, functionality, reliability, and performance. Meanwhile, 37 students answered the satisfaction survey questionnaire. The feedback and recommendations collected from the Evaluation stage from the experts and students were looped back to the design stage, where they were utilized to enhance the software prototype.

2.5 Data Analysis

Quantitative data analysis was employed in the study. The learning objectives were identified using frequency distribution for content analysis in the analysis stage, and the most necessary learning objectives were determined in the design stage. Moreover, the mean and standard deviation were employed to assess the levels of acceptability among experts regarding the software prototype and satisfaction among students during the evaluation stage. The mean scale, descriptive rating, and indicators for the levels of acceptability and satisfaction in the software prototype are found in Table 2. The standard deviation was employed to assess the variability among the responses gathered from both experts' acceptability and students' satisfaction levels. Students' feedback during the implementation and evaluation stages was analyzed using thematic analysis to identify, organize, and interpret recurring patterns and themes from the qualitative responses (Braun & Clarke, 2006). Table 2 shows the Acceptability & Satisfaction Scale.

Table 2. Acceptability & Satisfaction Scale

Mean Scale	Acceptability Rating	Satisfaction Rating
3.51 – 4.00	Very High – Minimal revisions needed	Excellent – Highly effective software
2.51– 3.50	High – Good but needs revisions	Sufficient – Meets training expectations
1.51 – 2.50	Low – Requires major modifications	Insufficient – Does not fully meet needs
1.00 – 1.50	Very Low – Software should be revised or discarded	Not Usable – Ineffective training tool

3. Results and Discussion

3.1 Analysis Stage

During the Analysis Stage, a researcher-made needs assessment questionnaire was administered to 37 purposively selected maritime students to determine the specific areas of COLREGs Rules 13–18 in which they experienced learning difficulties. The questionnaire contained learning objectives covering overtaking (Rule 13), head-on situations (Rule 14), crossing situations (Rule 15), actions by the give-way and stand-on vessels (Rules 16–17), and responsibilities between vessels (Rule 18). Students identified the competencies they found most difficult to understand and apply. The responses were analyzed using frequency distribution, which revealed that the highest frequencies were associated with overtaking, head-on, crossing situations, and responsibilities between vessels. These findings indicate that while students possessed a basic conceptual understanding of the Collision Regulations, they encountered difficulties in applying the rules to practical navigational scenarios. Consequently, the identified learning gaps established the need for an interactive, simulation-based instructional tool capable of bridging the gap between theoretical knowledge and practical decision-making. In addition, system requirements were established based on both user needs and technical feasibility. The software required the use of Unity for 3D simulation, C# programming through Visual Studio for maneuvering controls, and JSON for data storage. Hardware requirements included standard input/output devices and computers capable of supporting graphical simulations. These findings support the development of simulation-based instructional tools that promote experiential learning. According to Mayer (2021), learners benefit from interactive and visual environments that enhance cognitive processing and understanding.

3.2 Design Stage

The Design stage produced a comprehensive blueprint for the digitalized steering and sailing instruction platform, integrating core features identified during the Analysis Stage. The simulator was designed to closely replicate maritime conditions by incorporating environmental elements such as vessel traffic, navigational lights, wind, and currents. Steering controls were programmed to imitate realistic vessel maneuvering, and adjustable speed settings were added to support training accuracy. To enhance learning, the system included pop-up triggers that alerted users of improper maneuvers, a guided practice mode for demonstrating rule applications, and a challenge mode for independent problem-solving. A scoring system, restart function, and map guide were added to enhance interactivity, provide spatial orientation, and improve learner autonomy. A user log in system ensured individual access and progress tracking. These design elements responded directly to students' documented learning difficulties and were consistent with research indicating that well-designed, scenario-based maritime simulations promote learner immersion, bridge the gap between theory and practice, and improve the application of navigational knowledge and competencies (Jamil & Bhuiyan, 2021). Figures 1, 2, and 3 respectively show the software's log-in screen, scenario selection screen, and maneuvering screen.



Figure 1. Log-in screen.

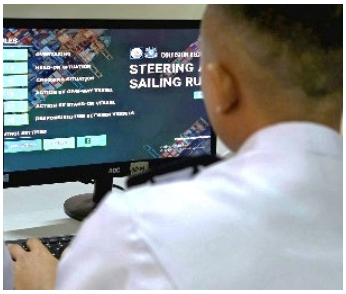


Figure 2. Scenario Selection Screen

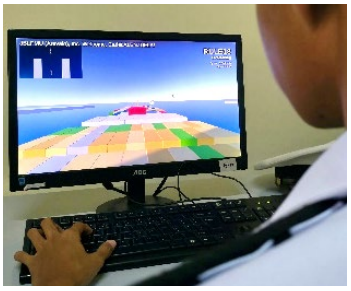


Figure 3. Maneuvering Screen

3.3 Development Stage

The Development Stage involved the creation of the functional software prototype based on the design specifications. The system was programmed using Unity, C#, and JSON, incorporating interactive elements to simulate real-time vessel maneuvering. The IT specialist programmed the simulator to operate across varying hardware capacities, resulting in three installation levels-minimal, intermediate, and advanced. The minimal installation required at least an i3 processor with 4-6 GB RAM using low quality design graphics; and the advanced version required an i7 processor with 10-16 GB RAM and high-quality simulation graphics. To ensure maximum accessibility, the software was developed for use on Windows, macOS, Android, and web-based platforms, enabling flexible deployment in diverse classroom and laboratory environments. Each student was assigned on PC to maximize individualized interaction with the mini-simulator, ensuring equal exposure to learning experience.

3.4 Implementation Stage

Student responses were coded into recurring themes, and the frequency of each theme was recorded. Coding was conducted manually by two members of the research team. Similar responses expressing the same idea were assigned identical codes. For example, comments referring to faster vessel movement, smoother speed adjustment, or more responsive maneuvering were grouped under the code "vessel speed and maneuvering controls." Related codes were subsequently clustered into broader themes. Disagreements in coding were resolved through discussion until consensus was achieved. It is important to note that the frequencies presented represent the number of coded responses per theme rather than the number of respondents, as individual participants were able to provide multiple feedback points. Participants shared their experiences of testing the software prototype, focusing on its usability, functionality, reliability and operational performance. Their feedback was analyzed to construct overarching narratives that reflected their collective and individual experiences, highlighting key strengths and areas for improvement. Qualitative responses collected during the Implementation and Evaluation stages were analyzed using Braun and Clarke's (2006) six-step thematic analysis. Responses were first familiarized through repeated reading. Initial codes were then assigned to meaningful statements. Similar codes were grouped into categories, from which preliminary themes were generated. Themes were reviewed, refined, named, and interpreted to represent common patterns across participants' responses. The thematic analysis revealed five major themes that reflect their learning experiences and recommendations for improving the developed simulation.

1. *Enhancement of Vessel Speed and Maneuvering Controls.*

   Student 35 recommended, “Modify the speed control system so that each spacebar press incrementally increases the ship's speed, rather than requiring constant pressure”.

2. *Realism and Accuracy of the Simulation Environment.*

   Student 10 commented, “The map is not accurate to the actual situation”, while students 3, 12, 22, and 33 recommended integrating GPS accuracy, environmental forces, navigational lights, and vessel traffic to replicate real-life conditions.

3. *Improved Interactivity and Gamification Features.*

   Student 14 said, “Create a practice mode with guided rule demonstrations and a challenge mode where students independently apply COLREGs without explicit prompts.

4. *Need for More Personalized Feedback and Error Correction.*

   Student 9 stated, “Add feedback in case the student failed in the first try”.

5. *Usability and Interface Improvements.*

   Student 25 explained, “Steering must align with the speed of the vessel—for example, when the vessel is slow, the steering must be slow also”.

Table 3 shows the summary of students' feedback on software prototype during Implementation Stage.

Table 3. Summary of Students' feedback on Software prototype during Implementation Stage

Theme	f	%
1. Enhancement of vessel speed and maneuvering controls	67	30
2. Realism and accuracy of the simulation environment	51	24
3. Improved interactivity and gamification features	50	23
4. Need for more personalized feedback and error correction	40	18
5. Usability and interface improvements	12	5

3.5 Evaluation Stage

The evaluation stage involved a second group of 37 students and 3 experts-a COLREGs instructor, a deck officer, and an IT specialist- who assessed the improved software in terms of usability, functionality, reliability, and performance. Results showed consistently very high acceptability across all dimensions. Students reported strong satisfaction, indicating that the software significantly enhanced their understanding and application of COLREGs rules 13-18. Experts affirmed the system's instructional value, noting that the digitalized platform improved simulation realism and offered a practical alternative to traditional lecture-based instruction. This stage assessed the developed software in terms of acceptability (experts) and satisfaction (students) using mean and standard deviation. Vessel maneuvering using digitalized instruction & students evaluating the digitalized instruction are shown in Figures 4 & 5 respectively.



Figure 4. Vessel Maneuvering using Digitalized Instruction



Figure 5. Students evaluating the Digitalized Instruction

3.5.1 Experts' Level of Acceptability of the Software Prototype

As an entire group, the software prototype obtained a mean (M) of 3.71 with a standard deviation (SD) of 0.42, interpreted as Very High. This indicates that experts perceived the software as highly acceptable and suitable for maritime instruction. The relatively low SD reflects consistency in their evaluations. Across all dimensions, the software received Very High ratings, indicating strong agreement regarding its usability, accurate functionality, reliability under varying conditions, and effectiveness in enhancing students' understanding of COLREGs Rules 13–18. These findings support the effectiveness of simulation-based instructional tools in technical education. According to Mayer (2021), interactive multimedia environments enhance learning by promoting cognitive engagement. Table 4 presents the level of acceptability of the developed steering and sailing software as evaluated by experts in terms of usability, functionality, reliability, and performance.

Table 4. Experts' Level of Acceptability of the Software Prototype

Dimension	Mean	Descriptive Rating	SD
Usability	3.74	Very High	0.39
Functionality	3.69	Very High	0.44
Reliability	3.65	Very High	0.46
Performance	3.76	Very High	0.38
Overall	3.71	Very High	0.42

3.5.2 Students' Level of Satisfaction of the Software Prototype

As an entire group, students obtained a mean (M) of 3.68 with a standard deviation (SD) of 0.45, interpreted as Very High. This indicates that students were highly satisfied with the software in terms of usability, engagement, and overall learning experience. Across all dimensions, the software consistently received Very High ratings, suggesting that students found the system intuitive, functional, reliable, and effective in improving their understanding of collision regulations. These findings indicate that students perceived the software as an engaging and effective instructional tool. Simulation-based learning environments have been shown to enhance motivation, comprehension, and skill development in complex domains such as navigation. Students' level of satisfaction with the software prototype is shown in Table 5.

Table 5. Students' Level of Satisfaction with the Software Prototype

Dimension	Mean	Descriptive Rating	SD
Usability	3.70	Very High	0.43
Functionality	3.66	Very High	0.47
Reliability	3.64	Very High	0.48
Performance	3.72	Very High	0.42
Overall	3.68	Very High	0.45

4. Conclusions

The development of a digitalized steering and sailing instructional software using the ADDIE model demonstrates significant potential in enhancing students' understanding in applying COLREGs Rules 13–18 within a classroom-based learning environment. The Analysis stage, based on frequency analysis of the needs assessment questionnaire completed by 37 students, identified learning gaps in applying overtaking, crossing, and head-on situations, and responsibilities between vessels. These findings confirmed the need for an accessible and simulation-based instructional tool to bridge theoretical knowledge and practical application. The Design and Development stages successfully produced a functional software prototype that integrates realistic maritime conditions, interactive maneuvering controls, and both guided and unguided scenario-based learning. The system is adaptable across multiple platforms and hardware configurations, making it suitable for flexible classroom implementation. During the Implementation stage, student feedback revealed experiential insights regarding system use, particularly the need for improvements in speed control, realism, interactivity, feedback mechanisms, and interface design. These findings provide valuable directions for further refinement of the system. The Evaluation stage indicated high levels of acceptability from both students and experts in terms of usability, functionality, reliability, and performance. These results suggest that the software effectively simulates real-world navigation scenarios and supports the development of learners' confidence and decision-making skills. Overall, the developed digitalized instructional software serves as a practical and effective supplementary tool for maritime education, strengthening students' understanding and application of COLREGs without requiring a full-mission bridge simulator. As cadets will soon encounter real watchkeeping duties and complex traffic situations at sea, it is essential that COLREG Rules are thoroughly taught not only through textbooks but also through realistic simulations, so the gap between classroom learning and actual bridge practice is minimized.

5. Limitations of the Study

This study has several limitations. It was conducted in a single maritime higher education institution with a limited number of expert evaluators, which may affect the generalizability of the findings. In addition, the results were based on participants' self-reported perceptions of acceptability and satisfaction rather than objective measures of learning outcomes, and the responses may have been influenced by novelty and social desirability biases. Future studies should involve multiple institutions, larger expert panels, and objective assessments to further validate the software's educational effectiveness.

6. Recommendations

Based on the results of the study, the following recommendations are proposed:

1. Enhance the software by improving vessel controls, incorporating more realistic simulation scenarios, and providing real-time feedback and performance summaries.

2. Adopt the software as a supplementary classroom instructional tool to complement the teaching of COLREGs Rules 13–18.

3. Conduct further validation involving multiple institutions, diverse student populations, and objective measures of learning outcomes to establish the software's educational effectiveness and broader applicability.

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Maritime English as a Safety Infrastructure: Towards Sustainable Communication Standardsin Digital Green Oceans

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Abstract: The maritime sector is undergoing a comprehensive transformation driven by digitalization, automation, and sustainability-oriented governance. In increasingly complex and multinational maritime operations, communication failures, linguistic asymmetry, ambiguity, and delayed responses remain important contributors to safety risk. This paper reconceptualizes Maritime English not merely as a phraseological competence based on Standard Marine Communication Phrases, but as a safety-critical coordination mechanism within maritime socio-technical systems. The study is designed as a conceptual framework and analytical demonstration paper rather than an empirical validation study. It proposes the AI-supported Vessel Integrated Maritime English (AVIME) framework as a future-oriented system architecture for monitoring, evaluating, and improving maritime communication performance. The proposed model introduces communication entropy as a conceptual indicator of communication degradation, structured around clarity, standard compliance, response time, and consistency. An illustrative Vessel Traffic Services scenario is used to demonstrate how communication performance could be assessed and how hypothetical entropy reduction could be calculated in future simulator-based or operational studies. The paper argues that, if developed and empirically validated, such a system could contribute to maritime safety by supporting real-time feedback, adaptive communication training, and systematic management of communication-related risk. The contribution of the study is therefore conceptual and methodological: it provides a foundation for future AVIME development, calibration, and empirical testing.

Keywords: Maritime English; sustainability; safety; digitalization; human-error, reconceptualization

1. Introduction

The maritime industry is undergoing rapid transformation driven by digitalization, automation, and operational complexity. Technologies such as smart shipping systems, digital twins, and Maritime Autonomous Surface Ships (MASS) are reshaping maritime operations into highly integrated socio-technical systems (Zeng et al., 2025; Xu and Guedes Soares, 2026). Despite these advances, human error remains a major contributing factor in maritime incidents, although contemporary safety theory interprets such errors as systemic outcomes emerging from interactions among human, technological, and organizational components (Dominguez-Péry et al., 2021; Sánchez-Beaskoetxea et al., 2021; Reason, 1990; Dekker, 2014). Within this framework, communication functions as a critical coordination mechanism supporting shared situational awareness and operational decision-making under uncertainty (Salmon et al., 2017). However, ambiguity, misinterpretation, delayed responses, and linguistic asymmetry remain major operational risks, particularly in multinational maritime environments (Yin et al., 2025). Efforts to reduce communication-related risks have primarily focused on the International Maritime Organisation (IMO) Standard Marine Communication Phrases (SMCP), designed to improve communication clarity and reduce ambiguity. Nevertheless, empirical studies indicate that SMCP implementation remains inconsistent in multicultural operational environments affected by language proficiency differences, time pressure, and situational complexity (Li et al., 2023; Abyan et al., 2025; Čulić-Viskota, 2024). Maritime communication therefore remains dynamic and context-dependent rather than strictly rule-based (Farjami, 2024). At the same time, advances in artificial intelligence, speech recognition, and natural language processing have enabled real-time communication analysis, adaptive feedback, and context-aware

maritime dialogue systems (Lall and Liu, 2025; El Salam Badawy, 2025; Veitch and Alsos, 2022; Nakilcioglu, 2025), while recent projects demonstrate the feasibility of LLM-supported maritime communication in autonomous vessel operations (Lundström et al., 2025; DASA, 2025). However, existing approaches remain fragmented and insufficiently integrated with socio-technical safety frameworks, revealing the absence of models linking communication performance to system-level safety outcomes (Abid et al., 2026; Gabedava and Hu, 2025). Accordingly, the central problem addressed in this paper is not the absence of Maritime English standards, but the absence of a measurable and adaptive framework for assessing how maritime communication deteriorates under operational pressure. Existing SMCP-based and simulator-based training approaches contribute to standardization; however, they do not sufficiently explain how ambiguity, delayed response, inconsistency, and loss of interpretive clarity can be continuously measured as system-level safety indicators. This paper therefore proposes the AI-supported Vessel Integrated Maritime English (AVIME) framework as a conceptual system architecture rather than as an already implemented platform. Its purpose is to demonstrate how Maritime English could be integrated with artificial intelligence, entropy-based assessment, and adaptive feedback mechanisms in a future maritime safety system. In doing so, the study reconceptualizes maritime communication as a safety-critical infrastructure and contributes a system-oriented conceptual framework linking communication, artificial intelligence, and digital maritime governance for next-generation maritime training systems (Karatuğ, 2025)

2. Literature Review

The literature review is organised around five interrelated themes: maritime safety and socio-technical systems; Maritime English and SMCP-based standardization; communication failures in multicultural maritime operations; artificial intelligence-supported maritime training; and entropy-based approaches to communication degradation. This structure is used to clarify the theoretical foundation of the proposed AVIME framework and to identify the specific research gap addressed by the present conceptual model. Maritime safety research has evolved from traditional approaches focused on technical reliability and procedural standardization (Rasmussen, 1997) toward a socio-technical systems perspective emphasizing interactions among human, technological, and organizational components (Vicente, 1999). Within this framework, safety is understood as an emergent outcome of complex system interactions, while communication functions as a critical coordination mechanism supporting shared situational awareness and adaptive decision-making. Contemporary maritime accident studies indicate that human error remains a dominant factor, although current human-factors research interprets such errors as systemic mismatches between human capabilities and operational demands rather than isolated individual failures (Grech et al., 2008). In complex maritime environments, ambiguity, incomplete information exchange, and delayed responses may gradually degrade coordination efficiency and increase system vulnerability, particularly under conditions of time pressure, environmental complexity, and cultural diversity. Within this context, Maritime English and the IMO Standard Marine Communication Phrases (SMCP) constitute the principal standardized communication framework for multinational maritime operations (IMO, 2022). Although SMCP improves clarity and consistency, empirical studies indicate persistent limitations related to language-proficiency differences, contextual variability, and operational complexity, which frequently lead to deviations from standardized phrases and increased ambiguity (Nursyam et al., 2025; Yin et al., 2025). Recent STCW-aligned SMCP training approaches partially address these issues (Amundsen and Noble, 2025), yet communication in maritime operations remains dynamic and insufficiently managed through static standardization alone. A major limitation in the literature is the absence of frameworks capable of measuring the continuous degradation of communication performance. In this regard, entropy theory provides a useful analytical perspective for understanding communication uncertainty and information degradation processes (Shannon, 1948). Communication entropy reflects the loss of clarity, coherence, and predictability within communication processes (Sogut and Yercan, 2025), yet entropy-based approaches to maritime communication remain largely unexplored. At the same time, advances in artificial intelligence and digital technologies have enabled adaptive maritime training systems capable of speech analysis, real-time feedback, and context-aware communication evaluation (Suresh, 2019; Chen et al., 2026; Reyes, 2026). AI is also increasingly integrated into autonomous maritime operations, where communication between human operators and intelligent systems becomes safety-critical (Porathe, 2021). Nevertheless, existing AI applications remain fragmented and weakly integrated with communication theory and socio-technical safety analysis (Albrecht, 2025). Accordingly, the main research gap does not lie in the absence of communication standards or maritime

training tools, but in the lack of an integrated framework capable of continuously assessing communication degradation as a safety-relevant system variable. Existing SMCP-based approaches support standardization, and simulator-based training contributes to experiential learning; however, neither approach sufficiently quantifies how ambiguity, delayed response, inconsistent phrasing, and loss of interpretive clarity accumulate under operational pressure. Similarly, emerging AI-supported tools offer opportunities for speech recognition and adaptive feedback, but they remain weakly connected to socio-technical safety theory and information-theoretic measurement. This study addresses this gap by introducing communication entropy as a conceptual construct and by proposing the AVIME framework as a future-oriented architecture for measuring, monitoring, and reducing communication-related safety risk. Unlike standardization-driven or technology-centric approaches, the proposed framework conceptualizes maritime communication as a dynamic, measurable, and safety-critical coordination process within maritime socio-technical systems.

3. Methodology

This paper adopts a conceptual framework development methodology. It does not report empirical data collection, prototype implementation, user testing, simulator experiments, or operational validation. Instead, the framework is developed through a theoretical synthesis of four knowledge domains: Maritime English and SMCP-based standardization, socio-technical safety theory, human-factors approaches to maritime error, and entropy/information-theoretic reasoning. The purpose of this methodology is to construct a future-oriented analytical architecture through which communication degradation could be measured and managed once the AVIME system is developed, implemented, and empirically validated. The proposed AVIME framework is therefore not presented as an operational system already tested at sea or in a simulator environment. Rather, it is presented as a pre-implementation conceptual architecture. The illustrative scenario and entropy calculation included in this paper are used to demonstrate the measurement logic of the framework, not to provide empirical evidence of system effectiveness. Empirical validation is reserved for future research phases involving simulator-based experiments, expert assessment, and analysis of authentic maritime communication data. The study is grounded in the socio-technical systems perspective, which conceptualizes maritime operations as dynamic systems composed of interacting human, technological, and organizational components (Leveson, 2011). Within this framework, communication is modelled as a coordination layer connecting human actors, technical systems, and organizational structures. This perspective shifts communication from a linguistic skill toward a system-level function enabling coordination and maintaining operational integrity. Communication entropy is defined as the progressive degradation of coordination efficiency within a maritime socio-technical system caused by ambiguity, inconsistency, delay, and variability in communication processes. This definition emphasizes that communication failures should be understood not as discrete events but as continuous degradation processes consistent with systemic interpretations of human error and performance variability (Hollnagel, 2017). Communication entropy is conceptualized through four dimensions: clarity (C_1), representing semantic precision and absence of ambiguity; standard compliance (C_2), representing alignment with SMCP and communication protocols; response time (C_3), representing temporal efficiency; and consistency (C_4), representing communication stability and uniformity. These dimensions are consistent with studies emphasizing communication clarity, standardization, and variability in maritime operations (Abyan, Supangat and Kuncowati, 2025). Together, they enable communication to be operationalized as a multidimensional performance variable. To operationalize communication degradation analytically, communication entropy is formulated as follows:

$$H_c = w_1(1 - C_1) + w_2(1 - C_2) + w_3 C_3 + w_4(1 - C_4) \quad (1)$$

where C_1 represents clarity score, C_2 represents SMCP compliance score and C_3 denotes normalized response time, C_4 represents communication consistency, w_i denotes weighting coefficients. This formulation enables communication performance to be quantified and compared across operational scenarios. To capture uncertainty in communication, the model is extended using Shannon entropy:

$$H_c = -\sum P(m_i) \log P(m_i) \quad (2)$$

where $P(m_i)$ denotes probability of correct interpretation of message m_i.

On this basis, the proposed AVIME framework is designed as a future system architecture rather than as an implemented and tested platform. It would integrate operational, communication, standardization, artificial

intelligence monitoring, and governance layers within a unified architecture intended to support real-time communication analysis, entropy evaluation, adaptive feedback, and performance management. In a future implementation, the system would combine speech recognition, natural language processing, SMCP validation, entropy calculation, feedback generation, and adaptive scenario modules within a closed-loop AI-assisted learning structure. Under this proposed logic, user-generated communication would be analysed through entropy-based evaluation, feedback, and scenario adaptation, enabling progressively improved communication training. Training would be based on realistic maritime scenarios characterized by operational complexity, uncertainty, multicultural interaction, time pressure, and safety-critical decision-making. The intended learning logic is reflex-based and adaptive, with the purpose of improving reaction speed, decision accuracy, and communication consistency through context-appropriate responses. Since the present study remains conceptual, future validation would be required through simulator-based comparisons between traditional and AI-supported training, expert assessment of communication quality, and analysis of authentic maritime communication data. Methodologically, the study integrates socio-technical systems theory, communication analysis, artificial intelligence, and adaptive learning within a unified framework bridging theoretical and operational dimensions (Wahl and Giskeødegård, 2025).

4. AVIME Conceptual Architecture

The conceptual model proposed in this study is based on a fundamental shift in perspective: maritime communication is not treated merely as a linguistic activity, but as a core coordination mechanism within maritime socio-technical systems. This shift allows communication to be conceptualized as a measurable system variable that can influence operational coherence, shared situational awareness, and safety performance. Within this framework, communication is understood as a governance-related function that connects human actors, technical systems, and organizational procedures. Any degradation in communication quality may increase uncertainty, weaken coordination, and contribute to operational risk. The proposed AVIME architecture is intended to operationalize this perspective in a future system by integrating communication processes, standardization mechanisms, artificial intelligence-supported monitoring, and adaptive feedback within a unified conceptual structure. In the proposed model, communication entropy represents the degree of disorder, uncertainty, or degradation within maritime communication processes. Unlike traditional approaches that focus mainly on discrete communication errors, the entropy perspective allows communication quality to be interpreted as a continuous and cumulative process. Within this framework, communication entropy is conceptualized as a composite construct integrating semantic clarity, SMCP compliance, response-time efficiency, and linguistic consistency.

Each dimension is assumed to contribute to the overall entropy level by reflecting a different aspect of communication performance. Conceptually, communication entropy may be represented as evolving dynamically under operational pressure:

$$H_c(t) = H_0 + \alpha t - \beta L(t) \tag{3}$$

where H_0 represents the initial entropy level, α represents the assumed entropy growth rate associated with stress, workload, ambiguity, or time pressure, β denotes the assumed learning or feedback effect, and $L(t)$ denotes the learning/feedback function over time. This formulation is not presented as an empirically calibrated dynamic model in the present paper. Rather, it illustrates the theoretical assumption that communication entropy may increase under operational pressure and may be reduced through learning, feedback, and standardization mechanisms. The proposed AVIME framework is structured as a multi-layered conceptual architecture linking operational scenarios, communication input, speech recognition, SMCP validation, entropy calculation, adaptive feedback, and governance-oriented performance monitoring. Figure 1 presents this structure as a future-oriented design logic rather than as an already implemented system.

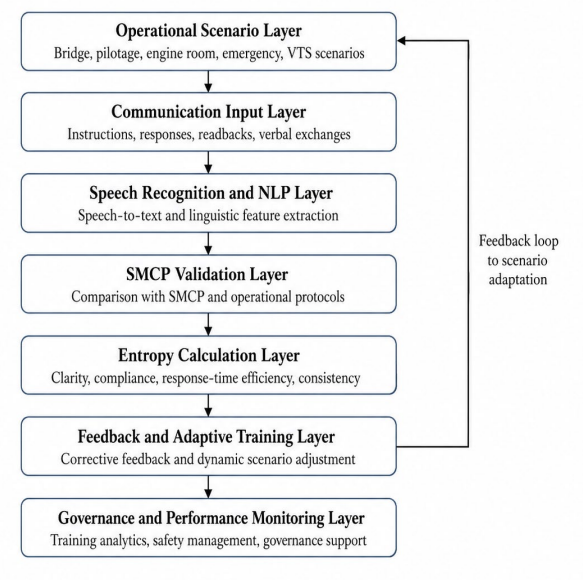


Figure 1. Conceptual architecture of the proposed AVIME framework.

As shown in Figure 1, AVIME is conceived as a closed-loop adaptive learning structure. If implemented in a simulator or operational training environment, user-generated communication would be analysed, entropy scores would be calculated, corrective feedback would be provided, and subsequent scenarios would be adjusted to support more precise, standardized, timely, and consistent maritime communication. These functions remain proposed system capabilities rather than implemented features in the present study.

5. Conceptual Demonstration and Discussion

This section provides an illustrative VTS scenario and a hypothetical entropy calculation to show how the proposed AVIME logic could be applied in future empirical studies. The illustrative scenario concerns Vessel Traffic Services (VTS) communication in a congested restricted-water environment involving time pressure, collision risk, course alteration, and multilingual crews. In a traditional condition, a vessel response such as "We are altering course slightly to port" is ambiguous because it lacks numerical precision and clear readback. In the proposed AI-supported condition, AVIME would function as an assistive monitoring layer by flagging this ambiguity and suggesting a more standardized response, such as "Altering course to port 15 degrees." This example is not presented as empirical evidence of AVIME's effectiveness, but as a conceptual demonstration of how communication degradation and corrective feedback could be represented. Table 1 presents hypothetical scores assigned only for illustrative purposes. The values are not derived from empirical measurement, simulator testing, prototype use, or operational communication data. They are included to demonstrate how the proposed entropy model could be applied once AVIME is implemented and validated. For consistency, all four performance dimensions are expressed on a normalized scale from 0 to 1, where higher values indicate better communication performance and lower expected entropy.

Table 1. Hypothetical communication performance scores for the illustrative VTS scenario

Metric	Traditional	AI-Supported
Clarity	0.50	0.80
SMCP Compliance	0.40	0.85
Response-time efficiency (C_3)	0.40	0.70
Consistency	0.60	0.80
Communication entropy (Hc)	**0.525**	**0.2125**

Entropy Reduction: $\boldsymbol{\Delta H_c = H_{baseline} - H_{AI} = 0.525 - 0.2125 = 0.3125.}$

Assuming equal weights, the traditional condition produces Hc = 0.525, while the proposed AI-supported condition produces Hc = 0.2125. The illustrative entropy difference is therefore ΔHc = 0.3125, corresponding to an indicative reduction of approximately 59.5% relative to the traditional condition. This percentage is hypothetical and should not be interpreted as an empirical result. Rather, it demonstrates how the proposed model could express communication improvement numerically when validated scores become available. The conceptual demonstration suggests that communication entropy may serve as an integrated metric for representing degradation across clarity, SMCP compliance, response-time efficiency, and consistency. The proposed AVIME framework may support maritime education, simulator-based training, and safety management through adaptive feedback and continuous monitoring. However, the framework remains conceptual and requires future validation through prototype development, simulator-based experiments, expert assessment, and authentic maritime communication data. AI should therefore be understood as an assistive tool supporting human operators rather than replacing professional judgement (Parasuraman and Riley, 1997).

6. Conclusion

This paper proposed AVIME as a conceptual architecture for treating Maritime English as a measurable safety-related coordination process. It showed how communication degradation could be represented through clarity, SMCP compliance, response-time efficiency, consistency, and hypothetical entropy scores. Future research should develop and validate the AVIME model through simulator-based experiments, expert assessment, and authentic maritime communication data.

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Transition from Traditional Ship Control and Management towards the MASS Concept: Pros and Cons

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Abstract: The maritime industry is entering a period of profound transformation in the history of maritime operations, driven by advanced digitalization, automation, and growing societal demands for safer and greener transport. Central to this transformation is the emergence of the Maritime Autonomous Surface Ship (MASS) concept, which challenges the long-established paradigm of ship control and management based on continuous human presence on board.

Historically, maritime operations have relied on human-centred shipboard control, with navigation, engineering, and safety management performed by trained seafarers embedded within the ship's operational environment. The MASS concept introduces a gradual redistribution of control among onboard automated systems, remote shore-based operators, and ultimately artificial intelligence (AI), fundamentally altering the nature of maritime work, responsibilities, and associated risks.

This paper analyses the transition from traditional ship control and management towards the MASS concept. In paper authors present the results of research through critically evaluation of its advantages and disadvantages not only in terms of technical capability and system design, but also through the lens of human performance, future Maritime Education and Training (MET) and seafarers' skills, maritime safety, situational awareness and system reliability.

Keywords: autonomous shipping; seafarers; maritime safety; system reliability

1. Introduction

Commercial shipping is fundamental to global trade, yet it faces increasing pressure to improve safety performance, reduce emissions, and enhance operational efficiency. At the same time, digitalisation and automation have accelerated across navigation, machinery control, and decision support systems. However, maritime operations continue to encounter crewing challenges, economic constraints, and the growing complexity of ship systems.

Traditional ship control and management are human-centred, relying on distributed expertise among the bridge team (navigation, collision avoidance, external communications, voyage monitoring), engine room team (propulsion, power management, preventive maintenance), and deck team (maintenance of the ship hull and deck equipment). These roles are integrated into daily operations alongside safety and emergency responsibilities (firefighting, abandoning ship, medical response, containment of hazardous situations). The value of this model lies not simply in humans "controlling the ship", but in human operators continuously integrating multiple cues (visual, auditory) to maintain situational awareness (SA). Nevertheless, traditional operations face persistent safety challenges linked to fatigue, workload, communication breakdowns, and organisational constraints. Accident investigations frequently identify "human error" as a contributing factor, yet modern safety science emphasises that human performance is shaped by system design, weak procedures, inadequate training, and organisational context (Reason, 1997; Hetherington, 2004; Mišković *et al*., 2022; Mišković *et al*., 2025).

MASS concept disrupts this paradigm by reconfiguring how ships are controlled and managed, shifting elements of decision-making from onboard crews to onboard automation and remote shore-based operators,

and potentially to AI-supported or AI-led control at higher autonomy levels (IMO, 2018). Potential benefits include reduced fatigue-related errors, improved consistency in routine operations, and enhanced occupational safety (IMO, 2021). Autonomy may also reduce human exposure to dangerous environments in certain operations. In the early stages, MASS autonomy often resembles advanced automation with remote oversight. Higher autonomy allows the ship to execute more decisions without direct human input, while humans supervise at a higher level and intervene in case of anomalies. To monitor such systems, it is assumed that traditional education and training for seafarers do not provide the necessary competencies for those who must not only understand all standard operating procedures for managing a ship, but also recognise potential anomalies in the management process and intervene promptly to prevent accidents at sea.

While technology is a central enabler, the MASS transition is not solely technological. It is a socio-technical change affecting safety models, legal responsibility, risk ownership, competence requirements, and the organisation of maritime work, which has traditionally relied on trained seafarers. Their continuous presence provides direct perception, onboard intervention capability, and embodied understanding of the vessel and its context. In contrast, remote operations rely on mediated sensing, networked communications, and software-defined control modes. This shift can create new failure modes, where human error is replaced by human-autonomy interaction problems, degraded situational awareness, and complex socio-technical coupling (Endsley, 2018; Hollnagel, 2014).

MASS should prevent the recurrence of incidents caused by seafarers operating ships in the traditional way. In this way, one of the causes of accidents at sea will certainly be avoided, but inevitably, during the transitional phase and implementation of such systems, the maritime industry will face a number of challenges arising from non-human errors, primarily caused by human error in the process of building a new autonomous ship management system.

This paper aims to:

- Describe how ship control and management evolve from onboard human control to MASS
- Evaluate potential advantages and disadvantages of MASS
- Analyse impacts on human performance and situational awareness across onboard and shore-based roles
- Discuss safety and reliability challenges
- Propose directions for MET modernisation and competency development.

Given the exploratory nature of this research and the ongoing development of autonomous maritime technologies, a narrative literature review was selected as the primary methodological framework. Following the literature review, logical synthesis and critical analysis was employed to compare conventional ship control and management models with autonomous operational frameworks.

2. From traditional shipboard control to distributed control in MASS

As stated, traditional shipboard control relied on trained seafarers, with well-known risk factors such as fatigue, communication breakdowns, coordination failures, skill variability, uneven exposure to rare emergencies, and economic pressures that may reduce crew size and increase workload, leading to human error. However, human error is often the final link in a chain that includes poor design, weak procedures, inadequate training, and latent organisational conditions (e.g. Mišković and Wang, 2025).

In 2018, the IMO established guidelines for MASS based on four levels of automation and autonomy (IMO, 2018). The MASS concept can be viewed as a continuum, where ships progress through increasing degrees of automation and autonomy, minimising the need for operator oversight (Ventikos *et al*., 2020). In the early stages, MASS autonomy often resembles advanced automation with remote oversight. Operationally, control may be distributed among:

- Level 1: Onboard automation (navigation support, collision avoidance logic, machinery automation)
- Level 2: Remotely controlled with seafarers onboard as backup

- Level 3: Remote Shore Control Centres - SCCs (monitoring, remote intervention, exception handling)
- Level 4: Fully autonomous (AI-based decision-making).

Higher autonomy allows the ship to execute more decisions without direct human input, maintain consistent watch-keeping functions, and support collision avoidance using fused sensor data (e.g. radar, AIS, EO/IR cameras, LIDAR). This distribution shifts the human role from direct manual control to supervisory control and exception management. Such changes have been studied extensively in other high-risk sectors (aviation, process industries), where supervisory control can lead to "out-of-the-loop" problems. In these cases, humans may be less able to detect anomalies and intervene quickly, especially when automation performs reliably most of the time (Endsley and Kiris, 1995; Parasuraman and Riley, 1997).

The MASS transition can be considered a change in work, not only technology (Cheng *et al*., 2024; Xiang *et al*., 2025). A key implication is that work content changes as control is redistributed:

- operators move from hands-on control to supervisory control
- decision authority becomes conditional; the ship acts unless intervention is required
- the "operational picture" is mediated through sensors, data fusion, and interface design.

Therefore, effective Human-Machine Cooperation is essential (Liu *et al*., 2022). This is important because MASS, while reducing some onboard human error modes, may amplify or create new ones. Risk is not eliminated but transformed, as these systems will be developed by experts mainly trained in automation. However, their remote control and monitoring will fall to seafarers or operators who currently lack the necessary competencies, since existing training programs do not adequately cover the management of such automated systems.

3. Situational awareness (SA) under autonomy and remote operation

Regardless of the level of ship operation, whether controlled by a seafarer or a remote-control operator, maintaining SA is essential for effective collision avoidance, emergency management, and safe navigation. Endsley (1995), in his model, defines SA in three levels:

- perception (data-driven)
- comprehension of their meaning (i.e. sensemaking)
- projection of future events and states.

In traditional settings, SA relies on direct observation (visual lookout, hearing signals), instrument interpretation (radar/ARPA, ECDIS, AIS), and contextual judgement (e.g. traffic patterns, local practices, weather, vessel handling characteristics). SA also depends on teamwork and communication on the bridge and with external parties (e.g. other vessels, VTS, pilots).

MASS does not remove humans; it changes where and how they work. In particular, remote operations fundamentally alter SA. The operator's perception is mediated through sensors and interfaces. Even with extensive sensor coverage, the operator may experience:

- reduced richness of cues, including subtle environmental indicators (glare, sea state nuances, motion cues)
- field-of-view constraints of cameras, especially at night or in poor weather
- latency and bandwidth variability, affecting the timeliness of perception and confidence in data
- sensor fusion uncertainty, where combined data may conceal inconsistencies rather than clarify them.

This can degrade Level 1 SA (perception), which then undermines comprehension and projection. In complex environments such as congested ports, mixed traffic with small craft, or unusual behaviour by other vessels, SA requirements are especially high. If remote SA is fragile, the "human in the loop" may only realise the severity of a situation once it has already escalated (*Han et al*., 2022; Cheng *et al*., 2024).

Higher automation can support SA by monitoring targets and presenting alerts, but it can also harm SA by encouraging passive monitoring and reducing active information seeking. Two well-known risks are:

- automation bias, where operators over-trust system recommendations and fail to cross-check (Parasuraman and Riley, 1997)
- mode confusion, where operators misunderstand the automation state, goals, or constraints (Endsley, 2018).

In MASS contexts, "mode awareness" becomes part of SA. Additionally, remote operations will involve human-autonomy teams rather than isolated human or machine action. Operators must understand not only the external maritime situation, but also the internal state of the autonomy stack (sensor health, confidence estimates, decision logic state, active constraints, failover modes). For HMC, this raises design questions:

- How will the system communicate its intent (planned manoeuvre, collision avoidance strategy)?
- How will uncertainties be displayed (sensor confidence, conflicting data)?
- How will handovers between autonomous control and human remote control be executed?

Additionally, a remote operator may supervise several ships and intervene only when thresholds are exceeded. This structure concentrates human decision-making into rare, time-critical situations, increasing cognitive demand and the likelihood of error. It also changes team coordination, communication patterns, and accountability structures. Therefore, analysing MASS requires linking technology, human cognition, and organisational design in an integrated view (Hollnagel, 2014).

Furthermore, in connected, software-defined ships, cyber threats become operational threats. In MASS operations, cyber can directly affect:

- sensor integrity (spoofing, manipulation)
- navigation signals (AIS and GNSS spoofing/jamming)
- remote control links and SCC infrastructure
- availability of decision support and autonomy services.

For situational awareness, cyber risk is particularly critical because manipulated data can create a false picture of reality. Thus, cyber resilience becomes inseparable from situational awareness and from MET. This adds cognitive complexity and creates a new training need: operators must develop SA about the ship as a cyber-physical system, not only the sea and traffic situation (e.g. Lynch *et al*., 2024; Xiang *et al*., 2025).

4. MASS and Maritime Training and Education (MET)

MASS adoption will fail or create unacceptable risk if training and competency frameworks lag behind operational change (Ceylan, 2025; Fan and Yang, 2023; Meštrović *et al*., 2024). Traditional MET has been shaped by onboard roles and STCW-aligned competence statements. MASS introduces new roles (SCC operator, autonomy supervisor, remote engineering support) and changes traditional roles (onboard crew may become smaller, more technical, or more maintenance-focused). However, safety benefits depend heavily on reliability and resilience (Mišković, 2022; Mišković, 2024). A system that performs well in nominal conditions but fails unpredictably under sensor degradation or cyber disruption can produce brittle safety. Hollnagel (2014) argues that modern risk often concerns performance variability and how systems adapt under changing conditions. Therefore, MASS safety cases must consider:

- how the ship behaves under partial sensor loss (e.g. camera obscuration, radar interference)
- what happens during communications outage (hold course, slow down, loiter, anchor, request assistance)
- how remote operators regain control and situational awareness after being "out of the loop"
- how software updates and configuration changes are controlled and verified.

In addition, the IMO has explored MASS within regulatory scoping and work streams, highlighting that the concept affects multiple IMO instruments and requires careful consideration of responsibilities and equivalency (IMO, 2023). Still, fundamental questions remain unresolved:

- Timeliness of intervention: can remote operators intervene quickly enough under degraded communications?

- Competency boundaries: what must a navigator know about software behaviour, sensors, AI limitations, and cyber risk?

These unresolved issues can slow adoption and create transitional risk. Therefore, MET must evolve in three dimensions:

- competency content (what must be learned)
- training methods (how it is learned)
- assessment and certification (how competence is validated).



Figure 1. Domains of Competence.

The following competency domains are central for MASS (Figure 1), with direct links to situational awareness and safe intervention:

- Human-autonomy teaming and supervisory control: Operators must understand automation limits, failure modes, and safe intervention strategies. This includes avoiding automation bias and maintaining calibrated trust (Parasuraman and Riley, 1997).
- Systems thinking and engineering literacy: Even navigation-focused operators will need a stronger understanding of systems of systems: sensors, networks, redundancy architecture, decision pipelines, and degraded-mode behaviour. Systems thinking supports better comprehension and projection in SA terms.
- Data literacy and uncertainty management: As remote SA is largely data-driven, operators must learn to interpret confidence measures, detect anomalies, and reconcile conflicting sources. Training should emphasise "healthy scepticism" and cross-checking practices.
- Cyber resilience as operational competence: Cyber training should not be limited to policy awareness; it should include operational symptoms, immediate containment actions, reporting, and recovery strategies aligned with safety management (IMO, 2021).
- Remote communication and coordination: SCC operations depend on structured communication with VTS, ports, pilots, emergency services, and potentially onboard technicians. This includes handover protocols, escalation ladders, and shared mental models.
- Ethical and legal awareness for autonomy contexts: As responsibilities are distributed across humans and algorithms, professionals need a practical understanding of accountability

boundaries, documentation requirements, and regulatory expectations, even while legal frameworks evolve (IMO, 2021).

Because SA is not merely "knowledge", but a dynamic cognitive skill, MET must train SA explicitly. Evidence from human factors research indicates that SA can be improved through targeted training, scenario exposure, and feedback, especially when training mirrors operational complexity (Endsley, 1995; Endsley, 2018).

Future training methods should also be considered. Traditional bridge simulators are necessary but not sufficient. MASS requires simulators that can replicate:

- multi-ship supervision
- alarm management and prioritisation
- realistic interface layouts and interaction patterns
- integrated cyber and communications degradations
- team coordination across roles (operator, supervisor, technical support).

To avoid fragmented training practices, MET governance should coordinate among:

- maritime academies and simulator centres,
- flag states and administrations,
- classification societies and insurers,
- technology vendors and SCC operators,
- shipping companies and unions.

The IMO's ongoing work on MASS indicates that regulatory alignment will be continuous (IMO, 2021). MET frameworks should therefore be modular, enabling updates as technology and regulation mature.

Operator competence should be assessed through performance in scenarios, not only written tests. Safety-critical industries increasingly favour scenario-based evaluation to capture decision-making, SA maintenance, and error recovery. This aligns with the need to validate "projection" and "resilience" rather than only procedural compliance.

However, a key challenge will be preventing operator skill atrophy. If remote operators rarely perform manual ship-handling, they may lose the basic skills needed when autonomy fails. The maritime sector can learn from aviation debates on manual flying proficiency under high automation (Pazouki *et al.,* 2018). MET should therefore include periodic manual control refreshers and crisis drills, even if such events are rare in real operations. This is essential to ensure credible recovery capacity.

5. Discussion and Conclusions

By integrating existing knowledge and critically evaluating current developments, the study provides a balanced assessment of the opportunities and challenges associated with the transition from traditional ship control and management systems to the MASS concept.

MASS represents a significant shift from embedded onboard control to distributed control across automation, shore operators, and potentially AI. This transition offers opportunities for increased efficiency, improved environmental performance, and a reduction in some fatigue-driven error pathways. Accordingly, it is reasonable to suppose that possible advantages of transitioning from traditional ship control and management to the MASS concept include the potential to reduce some operational costs, such as crew wages, general crew costs, stores, victualling, spares, sundries, and management fees. Furthermore, the automation of ship management contributes to the optimisation of sailing routes and, consequently, leads to fuel cost savings. As fatigue is a significant contributing factor to accidents, its elimination can also reasonably be expected to improve maritime safety in general.

However, despite these anticipated advantages, it is evident that the concept also introduces new socio-technical risks, particularly regarding the maintenance of situational awareness under remote, data-mediated perception and high automation. Automation bias, mode confusion, cyber threats, and degraded-mode failures can undermine safety if not addressed through system design and robust training. The central implication is that

autonomy does not eliminate the human element; it transforms it. Outstanding questions regarding authority and accountability include:

- who will be the “master” and what will their role and responsibility be under maritime law in remote or autonomous modes (MASS Code)?
- the role and responsibility of the “remote operator”?
- who is responsible when automation acts unexpectedly? (How is liability assigned among the shipowner, system provider, SCC operator, and classification bodies?)
- how are COLREGs interpreted when decision-making is shared with algorithms?
- what ethical constraints should guide autonomous system or AI behaviour in unavoidable collision scenarios?

From the current standpoint, it is difficult to believe that humans will be excluded from authority and accountability issues, as removing humans from operational loops risks eliminating the adaptability that enables systems to cope with unexpected conditions. Human operators are, and should remain, the final barrier, despite their limited capacity for intervention. As a result, Maritime Education and Training becomes a primary safety lever. MET must expand beyond traditional seamanship to include supervisory control, data literacy, cyber resilience, and human-autonomy teaming, supported by high-fidelity simulation and competence-based assessment. If the sector invests in MET modernisation and SA-centric operational design, MASS can progress in a controlled, safety-justified manner. Without such investment, autonomy risks shifting maritime safety problems from the bridge to the interface, from fatigue to brittleness, and from visible human error to opaque system failure.

Once MASS is regulated and implemented, the industry will likely operate mixed fleets of conventional vessels and MASS, as they will share waterways for an extended period. This transition will introduce additional risks, as operators of traditional ships may not be able to predict the behaviour of autonomous vessels, and vice versa. Ports and VTS must adapt procedures and communication protocols, and regulations may evolve unevenly across regions. Furthermore, it can be assumed that the greatest challenge for such vessels will be navigation in areas where yachts and recreational or leisure craft are present. A phased deployment strategy is therefore advisable. The first stage would focus on restricted-area autonomy, such as short-sea routes and controlled operational zones where risks can be managed more effectively, as with Yara Birkeland (YKG, 2024). The second stage would introduce hybrid crewing, combining onboard personnel with remote assistance while maintaining onboard fall-back systems for safety, in line with the proposed MASS Level 2 concept. In the third stage, autonomy would gradually expand into open-sea operations, supported by robust emergency protocols and reliable communication contingencies. Finally, broader integration would occur once regulatory frameworks, technical capabilities, and MET (maritime education and training) systems have matured and become aligned.

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Digital Approaches to Seafarer Certificate Renewal: Enhancing Flexibility and Objectivity in Knowledge Assessment

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Abstract: The current system for renewing seafarer certificates relies primarily on classroom-based refresher training, requiring a significant time commitment and reducing available rest periods. This approach affects work organization and generates additional costs for both training institutions and maritime companies. As the theoretical requirements associated with certification change only marginally over time, the efficiency of traditional training models has become increasingly questionable. The author argues that contemporary digital technologies offer a viable alternative for supporting the assessment of seafarers' theoretical knowledge and the certificate renewal process through a flexible, platform based digital environment accessible across different devices and operational settings. The proposed approach enables the delivery of learning materials and structured, time restricted knowledge assessments, ensuring a consistent level of difficulty, supporting result comparability, and reducing the risk of unfair practices through dynamic question selection and activity traceability. In addition to conceptual analysis, the article incorporates input collected through a targeted questionnaire distributed among maritime companies, educational institutions, and training centers, providing practical perspectives on the applicability of the proposed solution. The author concludes that the digitalization of certificate renewal processes has the potential to enhance efficiency, flexibility, and sustainability while maintaining compliance with established regulatory principles, as well as improving the objectivity of knowledge assessment and reducing time consumption and environmental impact within the maritime sector.

Keywords: seafarer certification, maritime education and training, digital assessment systems, platform based learning environments, maritime sustainability

1. Introduction

Seafarers serving on internationally trading vessels are required to hold valid certificates of competency and proficiency under the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) (International Maritime Organization [IMO], 1978, as amended). Most certificates carry a five-year validity period, and revalidation requires demonstration of continued professional development, most commonly through attendance at classroom-based refresher training delivered by approved training institutions. For many serving officers and ratings, this means periodic travel to a training centre, time away from the vessel, a significant time commitment, and the costs that both generate for maritime companies and individuals alike.

At the same time, the maritime sector is changing rapidly. Onboard systems, voyage data management and shore-based operations are all becoming more dependent on digital tools and connectivity. Against this backdrop, the administrative and educational structures governing seafarer certification have moved slowly. The core STCW framework dates to 1978, and while the 1995 and 2010 (Manila) amendments brought meaningful updates, the basic model of classroom-based refresher attendance has remained in place.

This paper examines whether a platform based digital environment could offer a viable alternative to classroom attendance for the theoretical knowledge component of STCW revalidation. To explore this, an original survey was conducted among maritime professionals, gathering views on the efficiency of the current system, the appetite for change, and the features that would make a digital approach acceptable. The findings are considered in light of the STCW regulatory framework and relevant IMO guidance on digitalisation in maritime documentation.

The theme of IAMU AGA26, Human-centred Digital Oceans: Educating Safe and Green Global Maritime Professionals, maps directly onto what this paper addresses. Applying digital methods to maritime education, and the sustainability gains that come from reducing unnecessary travel and time consumption, are both central to the argument made here.

2. Background and Literature Context

2.1 STCW Revalidation Requirements

Regulation I/11 of the STCW Convention requires seafarers holding certificates of competency to revalidate every five years. Revalidation may be achieved by demonstrating approved sea service, completing approved training, or passing an approved examination. In practice, the most common route is a short refresher course delivered in a classroom by an approved training institution, covering basic safety topics and operational refreshers.

The classroom model has real advantages: standardised delivery, face-to-face instruction, and the ability to include practical elements where required. However, the theoretical requirements associated with certification change only marginally over time. Officers with ten or fifteen years of active sea service are regularly sitting through material they have covered before and applied throughout their careers. Vessel rotations and leave cycles do not always align with training centre timetables, creating additional work organisation disruption. For the theoretical knowledge component of renewal, the efficiency of traditional training models has therefore become increasingly questionable.

Concerns about the adequacy of competency-based training have been raised within maritime education research for some time. Barnett (2005) noted that the gap between theoretical knowledge delivery and practical application remains one of the persistent challenges in maritime training design, a tension that a hybrid digital approach is well positioned to address.

2.2 Digital Assessment in Professional Certification

Computer-based and online assessment is now standard across many regulated professions. Aviation authorities including the European Union Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA) have long accepted computer-delivered theoretical knowledge tests for pilot licences. The United States Medical Licensing Examination moved fully to computer-based delivery in 1999. The maritime sector has been slower to follow, despite having access to the same technical infrastructure that made these transitions possible elsewhere.

The case for computer-based assessment in high-stakes contexts is well supported in the educational technology literature. Randomised question pools drawn from large item banks reduce the risk of question leakage without affecting measurement validity (Drasgow et al., 2006). A meta-analysis conducted by Means et al. (2010) found that students in online conditions performed modestly better on average than those receiving face-to-face instruction. This supports the validity of digital delivery for knowledge-based components of professional training. Concerns about examination integrity in remote settings can be addressed through logged session data, browser controls, and identity verification at the point of login.

2.3 Maritime Digitalisation and IMO Policy

The IMO has been engaging with digital questions across several of its committees. The E-Navigation strategy recognises the role of digital tools in safer and more efficient navigation, while work on Maritime Autonomous Surface Ships (MASS) and the digitalisation of certificates under FAL.5/Circ.39/Rev.2 (IMO, 2021) shows that the organisation is open to digital formats in official maritime documentation. The consolidated STCW Convention text, including the Manila Amendments (IMO, 2011), provides the current regulatory baseline against which any digital renewal mechanism must be assessed.

However, the STCW framework as it stands does not explicitly permit digital knowledge assessment as a standalone revalidation route. Flag state administrations have some discretion over which training and assessment methods they will approve, which creates variation across jurisdictions. A platform based digital environment for certificate renewal would therefore need to secure recognition from individual flag states under existing provisions, or await a formal STCW amendment at IMO level. Neither constitutes a rapid process; however, both represent viable regulatory pathways, as examined in the discussion section.

3. Methodology

3.1 Survey Design

A structured questionnaire was developed to capture views on both the current refresher training system and a proposed digital alternative. The instrument contained fifteen questions using two formats: a five-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree) for attitudinal questions, and Yes/No/Unsure responses for questions about practical feasibility and regulatory acceptability.

Questions were grouped around four areas: perceptions of current classroom-based refresher training; technical readiness and device access; preferred features of a digital platform; and views on regulatory compliance. The survey was distributed via Google Forms through professional maritime networks, including direct email to shipping company officers, LinkedIn contacts in the sector, and colleagues at the Estonian Maritime Academy.

3.2 Sample

Twenty complete responses were received. The respondent group included deck officers at various seniority levels (Chief Officers and Captains), navigational cadets, one shipping company CEO, and maritime academy staff. Six respondents were from Viking Line, a major Baltic Sea ferry operator, which gave some sector-specific concentration within the sample. Most respondents were based in Estonia or Scandinavia, which constitutes a geographical limitation of the study. The findings may not fully reflect the perspectives of maritime professionals operating in other flag state jurisdictions, crewing markets, or regulatory environments, and caution is therefore warranted in extrapolating results beyond the Northern European context.

The sample is modest and not randomly drawn. Results are therefore presented as indicative of stakeholder opinion within this professional group rather than as statistically representative of the broader population. It should also be noted that six of the twenty respondents were affiliated with a single organisation, Viking Line, which introduces a degree of sectoral concentration into the results. Taken together, the small and geographically concentrated sample, the organisational dominance of a single operator, and the descriptive nature of the analysis define the methodological boundaries of this study; findings should therefore be treated as a basis for hypothesis generation rather than definitive conclusions.

3.3 Data Analysis

Likert-scale items were analysed using arithmetic means and response frequency distributions. Yes/No/Unsure items were analysed by frequency count. Where differences appeared between operational seafarers and shore-based or academic respondents, these were noted in the results. The analysis is descriptive in nature and does not extend to inferential statistics or the examination of relationships between variables; this reflects the exploratory scope of the study and points toward more advanced analytical approaches in future research.

4. Survey Results

4.1 Perceptions of Current Refresher Training

Table 1 summarises results across the Likert-scale items. Respondents were broadly unenthusiastic about existing classroom arrangements. The statement that classroom-based refresher training is an efficient use of time returned a mean of 2.95, meaning the average respondent leaned toward disagreement. This was reinforced by the low mean of 2.45 for the question about whether theoretical content changes significantly between renewal cycles, suggesting that most respondents see the material as largely static from one certification period to the next.

Logistical difficulty scored more strongly. Travel and attendance requirements were rated as creating operational problems with a mean of 3.55, with 55% of respondents selecting 4 or 5. This fits with the sample profile: Viking Line officers on regular Baltic ferry rotations work to tight schedules, and finding a window for a shore-based course is not always straightforward.

Table 1. Likert-scale survey results (n = 20, five-point scale)

Survey Statement	Mean n=20	Interpretation
Q1. Classroom-based refresher training is an efficient use of time	2.95	Disagrees
Q2. Theoretical content changes significantly between renewal cycles	2.45	Disagrees
Q3. Travel/attendance creates operational difficulties	3.55	Agreement
Q6. Online assessments can be made sufficiently secure and tamper-resistant	3.95	Agreement
Q7. Dynamic question selection improves fairness	3.95	Agreement
Q8. Replacing classroom with digital assessment is acceptable	3.45	Slight agreement
Q10. More likely to complete renewal on time with flexible option	3.95	Agreement
Q11. Reducing travel contributes to environmental sustainability	3.95	Agreement
Q13. Objectivity improves with standardised digital platform	3.75	Agreement
Q15. Overall support for a digital renewal platform	4.10	Strong agreement

4.2 Technical Feasibility and Infrastructure

The technical readiness picture was clear. Ninety-five percent of respondents confirmed that seafarers in their organisation have reliable access to internet-connected devices. This matters because lack of device access has historically been cited as a reason why digital assessment could not work in maritime contexts. Among this sample, that objection does not hold.

Eighty percent of respondents also believed a digital renewal process would reduce costs, with only one person disagreeing. For shipping companies carrying the expense of training courses, travel reimbursement and crew scheduling around attendance obligations, this perception reflects a genuine financial stake in the outcome.

Table 2. Binary question results (n = 20)

Statement	Yes	Unsure	No
Q4. Seafarers have reliable device access	19 (95%)	—	1 (5%)
Q5. A digital platform would be technically feasible	15 (75%)	5 (25%)	—
Q9. Digital renewal reduces costs	16 (80%)	3 (15%)	1 (5%)
Q12. Digital system meets STCW compliance	10 (50%)	8 (40%)	2 (10%)
Q14. Activity traceability is important	19 (95%)	—	1 (5%)

4.3 Platform Design Preferences

Specific platform features received strong support. Dynamic question selection from randomised pools scored a mean of 3.95, reflecting an understanding that this approach improves fairness and limits the value of simply memorising a fixed question bank. Activity traceability (logged responses, timestamps, session data) was seen as important by 95% of respondents, which aligns with what flag state administrations would likely require before recognising any digital system.

Replacing classroom refresher training with structured digital assessment was seen as broadly acceptable, with a mean of 3.45. That is not a ringing endorsement, but it does suggest there is no deep institutional resistance to the concept, at least among the people surveyed.

4.4 Regulatory Concerns

The clearest tension in the results was around regulatory compliance. Only 50% of respondents were confident that a digital assessment system could meet STCW revalidation requirements, while 40% were unsure and 10% disagreed. This is a striking contrast with the overall support figure of 4.10. People want the system to work, but many are not certain that it can legally.

This points to the core challenge: the barrier is not resistance to technology or cultural inertia, but a genuine question about whether digital assessment can be recognised as an approved examination or approved training under STCW Regulation I/11. That is a regulatory question, and it needs a regulatory answer.

5. Discussion

5.1 Conceptual Framework for the Proposed Platform

On the basis of the survey findings and the regulatory context described above, this paper sets out a conceptual framework for a platform based digital environment supporting seafarer certificate renewal. The proposed approach covers the theoretical knowledge component of STCW refresher obligations through structured, time restricted knowledge assessments accessible across different devices and operational settings. It does not replace the practical elements required by certain certificate types.

This distinction matters. STCW revalidation requirements vary significantly by certificate type. An Officer of the Watch revalidation, for example, encompasses both theoretical knowledge updates and practical competency elements such as Basic Safety Training refreshers, Global Maritime Distress and Safety System (GMDSS) procedures, and survival craft handling. These practical components require physical demonstration and cannot be delivered through a digital environment. The proposed model therefore adopts a hybrid structure: the theoretical assessment is completed online through the platform based environment, while any required practical elements are conducted at the nearest accredited training centre. Under this arrangement, a seafarer who previously spent three days attending a full refresher course would instead complete the theoretical assessment remotely in advance and attend a condensed one-day practical session locally. This reduces travel demands and work organisation disruption without compromising the integrity of practical competency verification.

The platform framework is built around five design principles, each of which supports result comparability and reduces the risk of unfair practices.

- Dynamic question selection: Questions are drawn at random from large item banks organised by competency area and aligned with IMO Model Course syllabi. No two assessment sessions are identical, ensuring result comparability while limiting the scope for memorisation of fixed question sets.
- Activity traceability: All interactions are logged with timestamps, IP addresses and device identifiers. Completion certificates are digitally signed and verifiable by flag state administrations and training institutions.
- Identity verification: Multi-factor authentication, with government-issued document checks at account creation and periodic verification during sessions, supports the integrity of the assessment process.
- Competency alignment: Assessment content maps directly to the minimum knowledge requirements in the STCW Code Tables A-II/1, A-III/1 and related tables, maintaining compliance with established regulatory principles.
- Flexible access: Assessments are available on demand across different devices, allowing seafarers to complete the theoretical component during leave or between rotations without mandatory travel to a training centre.

5.2 Regulatory Pathway

Two routes to regulatory recognition exist, and both are worth pursuing in parallel. The first operates at flag state level: administrations with delegated authority under STCW can designate approved assessment providers, and some already recognise computer-based theoretical examinations within their competency assessment frameworks. A pilot recognition by a forward-leaning flag state would provide concrete evidence for broader IMO-level consideration. Estonian Transport Administration, which has demonstrated openness to

digitalisation in maritime documentation, is a practical candidate for such a pilot given its proximity to this research.

The second route involves a formal STCW amendment through the IMO's Maritime Safety Committee. This is a longer process given international convention cycles, but it would deliver universal applicability across all flag state jurisdictions. Preparatory work could begin through MSC correspondence groups and regional bodies such as the European Maritime Safety Agency (EMSA), which already holds a mandate covering digital maritime certificates under Directive 2008/106/EC and its amendments.

5.3 Environmental and Operational Efficiency

Survey respondents showed strong agreement (mean = 3.95) that reducing travel associated with certificate renewal contributes meaningfully to environmental sustainability. This aligns with the IMO's 2023 Greenhouse Gas Strategy, which targets net-zero maritime emissions by or around 2050 (IMO, 2023). While an individual training trip generates modest emissions in isolation, the aggregate effect across approximately 1.89 million seafarers globally (BIMCO/ICS, 2021) adds up to a considerable environmental footprint. The hybrid model proposed here, where theoretical assessments are completed remotely and practical sessions are condensed and conducted locally, reduces time consumption and environmental impact within the maritime sector without removing the in-person elements that regulatory frameworks require.

6. Conclusions

The survey evidence presented in this paper suggests that maritime professionals are ready for a platform based digital environment supporting STCW certificate renewal knowledge assessment, both in terms of available technology and willingness to use it. Overall support for such an approach scored 4.10 out of 5. Device access is near-universal. Most respondents expect digitalisation to reduce costs. Design features including activity traceability and dynamic question selection are seen as appropriate and necessary for result comparability and fairness. As an exploratory study, this work establishes a meaningful foundation for more extensive future investigation rather than claiming definitive generalisable conclusions.

The main obstacle identified is regulatory. Half of respondents were not confident that a digital system could satisfy STCW revalidation requirements, and this uncertainty must be resolved before any platform can be widely adopted. The hybrid model proposed in this paper, combining remote theoretical assessment with condensed local practical sessions, offers a realistic path that maintains compliance with established regulatory principles while delivering meaningful gains in efficiency, flexibility, and sustainability.

Future research should include larger surveys across a wider range of nationalities and flag states to build a more representative picture of industry opinion. A legal analysis of flag state discretion under Regulation I/11 would clarify what is already permissible without a convention amendment. A pilot implementation in cooperation with an approved training institution would generate the practical evidence base that any regulatory argument will ultimately require. Beyond these steps, future work should explore statistical relationships between respondent profiles and platform acceptance, and examine the technical architecture required for a compliant digital assessment system. Comparative analysis of flag state regulatory frameworks would also help identify the most viable early-adoption jurisdictions.

The digitalisation of seafarer certificate renewal is not simply a matter of convenience. It is an opportunity to improve the objectivity of knowledge assessment, reduce time consumption and environmental impact within the maritime sector, and make the certification system more accessible and responsive to the realities of how seafarers actually work. In this sense, the move toward a platform based digital environment is also a human-centred one: it returns rest time to seafarers, reduces unnecessary disruption to work organisation, and puts the individual professional, rather than the logistics of attendance, at the centre of the renewal process.

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Qualitative risk analysis on the use of SMR for maritime nuclear propulsion using HAZID and HAZOP methodologies

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Abstract: The growing demand for safe, sustainable and low-carbon energy solutions has renewed interest in nuclear propulsion systems, particularly those based on Small Modular Reactors (SMRs) (Hannaford, 2022; European Commision, 2023). Due to their compact size, modularity, scalability and passive safety features, SMRs are considered a promising option for maritime propulsion and onboard power generation (Zohuri, 2023). However, their implementation in complex maritime environments requires systematic safety and operational risk assessment across design, operation and maintenance phases.

This paper presents a qualitative risk analysis of a reference SMR for maritime nuclear propulsion using a combined HAZID (Hazard Identification) and HAZOP (Hazard and Operability Study) approach (International Standards Organization, 2017; European Committee for Electrotechnical Standardization, 2019). The aim is to evaluate safety and reliability by identifying hazards, failure modes, process deviations, causes, consequences and safeguards.

Following a literature review on nuclear safety, SMR design and qualitative risk assessment, a representative SMR is selected and characterised, focusing on critical systems and operational parameters. HAZID is applied to identify hazards, threats and risk scenarios, enabling preliminary risk classification and mitigation strategies. In parallel, HAZOP systematically examines process deviations using guide words such as “more”, “less” and “none”.

The results highlight the complementary value of both methods: HAZID is effective for high-level hazard identification and early design decisions, while HAZOP offers a detailed analysis of operational deviations and system behaviour. Their combined use strengthens risk assessment and supports the development of safer, more reliable and environmentally sustainable SMR-based maritime nuclear propulsion systems.

Keywords: Nuclear propulsion; Small Modular Reactors (SMR); Qualitative risk analysis; HAZID and HAZOP; Maritime safety.

1. Introduction

The decarbonization of maritime transport is one of the major engineering and regulatory challenges facing the shipping industry. The continued dependence on fossil fuels contributes directly to greenhouse gas emissions, air pollution and long-term climate instability, while also exposing maritime operations to fuel-price volatility and supply vulnerabilities. In this context, nuclear energy has regained attention as a high-density, low-carbon option capable of providing continuous power with very low direct CO_2 emissions (Lee, 2024; Nøland et al., 2024; Van Hee et al., 2024; International Atomic Energy Agency, 2025).

Small Modular Reactors (SMRs) have become particularly relevant in this debate. Compared with conventional large nuclear power plants, SMRs offer reduced size, standardization potential, modular construction and, in many concepts, enhanced passive safety features. These characteristics make them attractive not only for land-based electricity generation but also for demanding applications such as remote installations, industrial heat supply and, potentially, maritime propulsion (Locatelli et al., 2013; Lee, 2024; Nøland et al., 2024; Generation IV International Forum (GIF), 2025; International Atomic Energy Agency, 2025).

At the same time, the integration of nuclear systems into ships requires rigorous attention to safety, operability and regulatory acceptability. Maritime systems operate in constrained spaces, dynamic environments and mission-critical conditions, where design robustness and risk-informed engineering decisions are essential. For this reason, the present work is framed not only by the potential advantages of SMRs but also by the need to understand the technological basis of advanced reactors and the theoretical foundations of risk analysis before moving to detailed methodological applications.

2. Nuclear Reactors

From the standpoint of neutron energy spectrum, nuclear reactors can be broadly divided into thermal reactors and fast reactors. Thermal reactors rely predominantly on low-energy neutrons and therefore generally use moderators to reduce neutron energy and increase the effective probability of fission in fissile isotopes such as uranium-235. Owing to their maturity and extensive operational experience, thermal reactors remain the dominant category in commercial nuclear power generation (Locatelli et al., 2013; Leray, 2024; Kiegiel et al., 2025).

Fast reactors, by contrast, operate with high-energy neutrons and intentionally avoid moderation. Their design seeks to preserve neutron energy by using coolants that do not significantly slow down the neutron population, such as sodium, lead or helium. This allows a more efficient use of fuel, the possibility of breeding fertile materials into fissile isotopes, and improves management of long-lived actinides, although at the cost of increased design complexity and, in many cases, more demanding fuel and materials requirements (Schulenberg et al., 2009; Allen and Crawford, 2007; Locatelli et al., 2013; Aoto et al., 2014; Kiegiel et al., 2025).

In response to the limitations of earlier generations of reactors, the Generation IV International Forum (GIF) identified six advanced reactor systems with strong long-term potential: the Very High Temperature Reactor (VHTR), the Sodium-cooled Fast Reactor (SFR), the Supercritical Water-cooled Reactor (SCWR), the Gas-cooled Fast Reactor (GFR), the Lead-cooled Fast Reactor (LFR) and the Molten Salt Reactor (MSR) (Generation IV International Forum (GIF), 2026).

These reactor systems were selected due to their potential to improve sustainability, economics, safety and proliferation resistance relative to earlier reactor generations.

Each of these concepts presents different advantages and constraints. VHTR systems are attractive for high-temperature industrial applications and hydrogen production, but their low power density and large graphite-moderated cores can complicate compact integration. SFR systems offer excellent heat transfer and strong fast-spectrum fuel utilization but present well-known sodium reactivity challenges in the presence of air and water. SCWR systems have a high thermodynamic efficiency but operate under very demanding pressure conditions. GFR systems benefit from inert gas cooling and high outlet temperatures, though heat removal is more challenging. LFR systems combine low-pressure operation with good heat transfer properties but face substantial materials and corrosion issues (Schulenberg et al., 2009; Allen and Crawford, 2007; Locatelli et al., 2013; Aoto et al., 2014; Generation IV International Forum (GIF), 2026; Kiegiel et al., 2025).

Although not all Generation IV systems are necessarily SMRs, the SMR paradigm has become central to the current development of advanced nuclear energy systems. SMRs are generally characterized by lower unit power output, modular design philosophy, factory-oriented fabrication potential and greater deployment flexibility. These attributes align well with maritime design constraints, where compactness, energy density, reliability and reduced onboard complexity are highly valuable (Nøland et al., 2024; Van Hee et al., 2024).

Within the broad family of advanced reactor systems, the Molten Salt Reactor stands out as a particularly relevant reference case for maritime propulsion studies. In MSRs, molten salts act as coolant and, in some configurations, also as the medium in which the fuel is dissolved. This distinguishes them fundamentally from conventional reactors based on solid fuel elements. Depending on the core design, MSRs may operate in thermal or fast neutron spectra, with or without graphite moderation (Serp et al., 2014; Park et al., 2024).

MSRs are widely discussed in literature because they combine high operating temperatures with relatively low system pressure. The favourable thermophysical properties of molten salts, including high thermal stability, high heat capacity and low vapours pressure, allow operation at elevated temperature without the need of high pressurization levels typical of water-cooled systems. This can reduce the severity of pressure-driven accident scenarios and support efficient heat transfer. Additional advantages often associated with MSRs include fuel-

cycle flexibility, the possibility of online refuelling in liquid-fuel configurations, more homogeneous fuel distribution, and the use of passive safety provisions such as freezer-plug-based drain systems. At the same time, major engineering challenges remain, especially those related to material corrosion, salt chemistry control, management of fission products dissolved in the salt, and the qualification of structural materials under coupled thermal, chemical and radiological stress (Locatelli et al., 2013; Serp et al., 2014; Drosińska–Komor et al., 2025).

From a maritime perspective, low-pressure operation and potentially compact system architectures make MSR especially attractive. Recent studies on marine nuclear applications identify MSR as strong candidates for future decarbonized propulsion because they combine high energy density with passive safety potential and long autonomous operation between refuelling intervals (Park et al., 2024; Drosińska–Komor et al., 2025).

3. Risk Analysis

The analysis of risk is a central part of the safety assessment of complex engineering systems. It provides a structured basis to identify hazards, understand possible consequences, and support design or operational measures aimed at prevention, control and mitigation. In the context of innovative maritime nuclear systems, a strong theoretical foundation in risk analysis is required before the study moves to subsystem-level hazard identification or process-deviation analysis (Siddiqui et al., 2017; Simmons et al., 2017).

Risk assessments are commonly divided into qualitative and quantitative categories, depending on how risk is described and on the nature of the information used. Qualitative risk analysis is based on the structured identification of hazards, causes and consequences, relying primarily on engineering judgement, expert knowledge and systematic scenario construction. Its principal strength lies in helping answer the question of what can go wrong, even when detailed statistical data are limited or unavailable (Siddiqui et al., 2017; Simmons et al., 2017).

Quantitative risk analysis, on the other hand, seeks to represent risk numerically through probabilities of failure, frequencies of occurrence and consequence modelling. This type of analysis can provide more precise estimations of risk magnitude, but it depends heavily on the availability of robust datasets, validated failure models and sufficient operational experience. For emerging technologies such as advanced maritime SMRs, those conditions are not always present, especially at early design stages (Simmons et al., 2017).

For this reason, qualitative risk analysis is usually more appropriate during the conceptual and preliminary design phases of innovative systems. It supports the early recognition of critical scenarios, helps to prioritise the most important vulnerabilities. In the present study a qualitative risk analysis on the introduction of MSR in vessels propulsion system is performed.

Among qualitative risk assessment techniques, HAZID (Hazard Identification) and HAZOP (Hazard and Operability Study) are widely recognised in process and safety engineering. HAZID is generally used as an early-stage hazard identification method. It provides a broad and structured mapping of relevant hazards, plausible causes, potential consequences and existing safeguards. As such, it is particularly suitable for preliminary studies in which the main objective is to organise safety thinking and identify the areas that require deeper investigation (Siddiqui et al., 2017).

HAZOP, in contrast, is a more detailed and systematic study of deviations from design intent. It is based on the division of the system into analysis nodes and on the combination of process parameters with guide words to generate plausible deviations from normal operation. These deviations are then analysed in terms of causes, consequences, safeguards and recommendations. This makes HAZOP especially valuable for understanding how a system may evolve from intended operation towards abnormal or unsafe states (Siddiqui et al., 2017; Jan Maciej Koscielny et al., 2017; Chisholm et al., 2018).

The two methods are therefore not competing alternatives but complementary tools. In advanced nuclear applications, and especially in systems such as MSRs where thermal, hydraulic, chemical and radiological phenomena are strongly coupled, a broad hazard-identification stage and a more structured deviation analysis are both conceptually relevant.

4. Methodology

Based on a deep literature review, within the family of Generation IV systems, the MSR was selected as reference reactor, since it seems to be the most suitable concept for vessel marine nuclear propulsion due to its low-pressure operation, high thermal efficiency potential and passive safety provisions (Serp et al., 2014; Chisholm et al., 2018; Drosińska–Komor et al., 2025). The system boundaries were then defined to identify the functional parts of the reactor to be considered in the analysis.

The methodology is based on studies from the literature where HAZID and HAZOP techniques are applied, adapted to current technological developments, namely on the specific features of MSR-based maritime propulsion. Both techniques are applied complementarily to assess risks. Given the innovative nature of the system and the limited operational data available, a qualitative approach enables the early identification of hazards, vulnerabilities and safety barriers prior to further quantitative refinement (Siddiqui et al., 2017; Simmons et al., 2017; Watson, 2009; International Atomic Energy Agency, 2018).

The selected system was divided into subsystems/nodes: (1) reactor core and reactor vessel, (2) primary circuit and pump, (3) primary heat exchanger, (4) intermediate circuit, (5) steam generation and power conversion system, (6) off-gas system, (7) freeze plug and drain line, (8) drain tank and associated passive system, and (9) chemical conditioning unit. This node division was adopted because it reflects the main operational and safety-relevant functions of the MSR system and provides a suitable basis for a systematic hazard and deviation analysis (Rausand, 2011; Siddiqui et al., 2017; Chisholm et al., 2020).

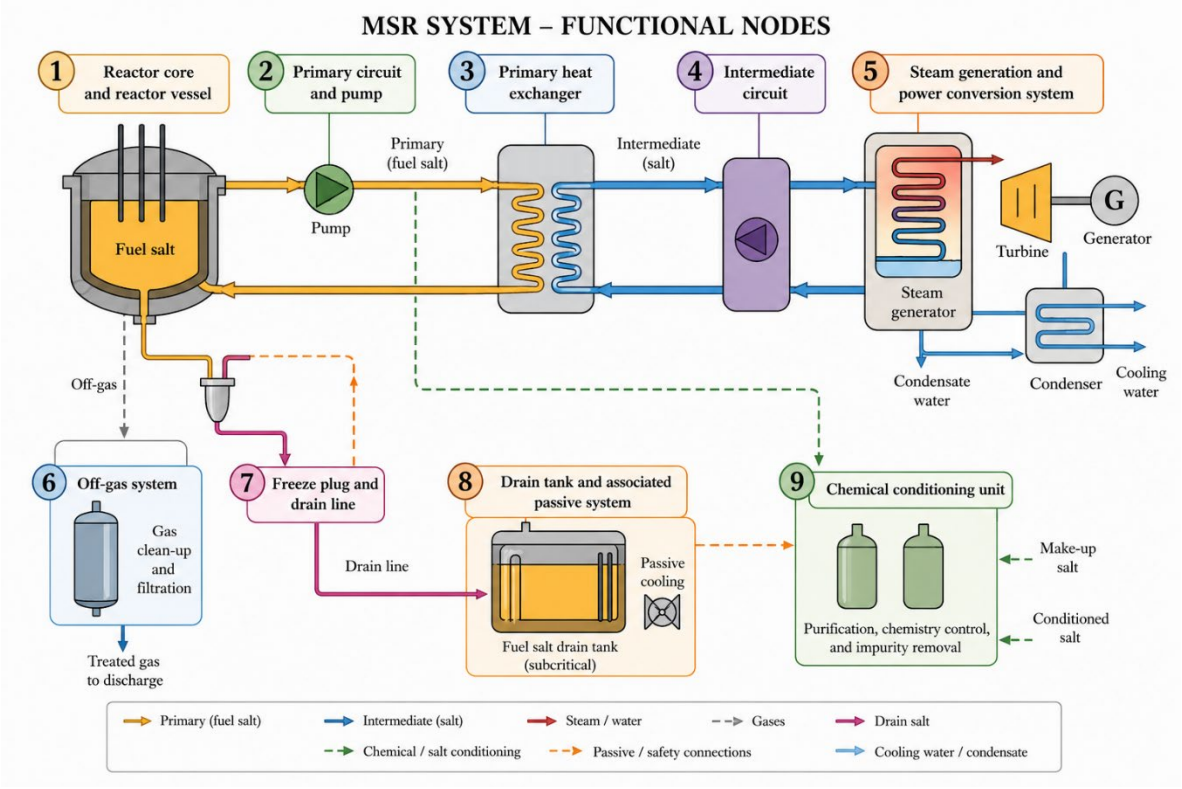


Figure 1. Nodes of MSR Reactor (Image generated with AI).

5. Results and Discussion

The HAZID study provided an initial high-level identification of the most relevant hazards associated with the selected MSR concept for maritime propulsion.

At node level, the analysis identified the risk of core overheating and abnormal reactivity conditions in node 1, and loss of molten salt circulation, leakage and local solidification in node 2, as the most significant hazards due to their direct impact on heat removal and system stability. Nodes 3 and 4 highlighted the importance of maintaining heat transfer continuity and circuit integrity, particularly in relation to the performance of barriers between primary and intermediate systems. In node 5, the main concerns were

associated with the conversion of heat into useful power and the management of residual heat under disturbed conditions.

Nodes 6, 7 and 8 were identified as especially relevant from a safety perspective, as they are directly linked to gas removal, emergency drainage and passive decay heat removal. Finally, node 9 emphasised the importance of chemistry control, impurity limitation and corrosion prevention for long-term system integrity.

Overall, the HAZID results confirmed that the selected MSR concept presents a safety profile strongly influenced by coupled thermal, hydraulic, chemical and radiological phenomena. In addition, the method proved to be an effective screening tool for identifying critical areas requiring further detailed analysis in the HAZOP stage.

When incorporating the maritime propulsion perspective, a clear differentiation in operational impact emerges. Nodes 1, 2, 7 and 8 concentrate the scenarios with critical impact, as they are directly associated with reactor safety and propulsion continuity. Nodes 3, 4 and 5 present mainly direct or indirect impacts, linked to reduced efficiency or partial loss of power. The off-gas system (node 6) stands out due to its potential for critical impact associated with radiological consequences, while node 9 is characterised by progressive effects on system reliability rather than immediate operational disruption.

The HAZOP study enabled a systematic analysis of deviations from intended operating conditions in each node. Compared with the HAZID stage, HAZOP provided greater analytical depth by linking parameters, guide words, deviations, causes and consequences in a structured manner.

At node level, the analysis identified temperature and reactivity increases in node 1, and reduced or no flow conditions in node 2, as the most critical deviations due to their direct impact on core heat removal and system stability. In nodes 3 and 4, deviations affecting heat transfer efficiency, circuit integrity and thermal transport stability were found to be central, while node 5 deviations were mainly associated with steam generation and power conversion, directly influencing plant operability and energy efficiency.

Nodes 6, 7 and 8 were highlighted from a safety perspective, particularly due to deviations related to gas management, passive emergency drainage and decay heat removal. Finally, node 9 deviations in salt composition and chemical control were identified as relevant for long-term system integrity, mainly through corrosion and material degradation mechanisms.

Overall, the HAZOP results provided a detailed interpretation of process behaviour and showed that the most safety-relevant deviations are those that compromise heat removal, fuel salt confinement, passive safety response, gas management and chemistry control.

When incorporating the maritime propulsion perspective, the analysis highlights a clear differentiation in operational impact. Nodes 1, 2, 7 and 8 concentrate the scenarios with critical impact, as they directly affect both reactor safety and power generation continuity, potentially leading to total loss of propulsion. Node 5 is mainly associated with indirect impacts, linked to efficiency and performance degradation, while node 6 stands out due to its potential for critical impact associated with radiological consequences. Node 9, in contrast, is characterised by progressive effects on system reliability rather than immediate operational disruption.

In methodological terms, HAZOP proved especially valuable for clarifying cause-consequence paths and for identifying where additional design measures or operational safeguards may be needed. The comparison between HAZID and HAZOP, Table 1, confirms the complementary nature of both methods.

HAZID was effective in establishing a broad overview of the main hazards affecting the selected MSR concept, helping to structure the overall safety picture and prioritise critical areas. Its principal strength lies in its ability to provide an early-stage and system-wide map of hazards without requiring a detailed parameter-by-parameter treatment. HAZOP, by contrast, provided greater resolution at node level by focusing on deviations from design intent.

Table 1. Comparison between HAZID and HAZOP.

Aspect	HAZID	HAZOP
Main objective	Preliminary identification of hazards and critical areas.	Systematic analysis of deviations from design intent.
Unit of analysis	Functional areas / nodes considered at a broad level.	Individual nodes analysed through parameters and guide words.
Level of detail	General and screening oriented.	Detailed and deviation oriented.
Main output	Hazards, causes, consequences, safeguards and recommendations.	Deviations, causes, consequences, safeguards and recommendations.
Main strength	Rapid system-wide understanding.	Greater analytical depth and clearer traceability.
Main limitation	Lower operational detail.	More time-consuming and methodologically demanding.

To further illustrate the practical application of the HAZOP methodology, Table 2 presents an example of how a process deviation is generated through the combination of a node parameter and a guide word. Unlike HAZID, which identifies hazards at a broader system level, HAZOP systematically explores deviations from normal operating conditions by applying guide words to specific process parameters.

Table 2. Example of a HAZOP deviation generated by combining a process parameter with a guide word.

Node	Parameter	Guide Word	Deviation	Possible Causes	Potential Consequences
Reactor core and vessel	Temperature	More	Higher-than-intended core temperature	Excess reactivity; insufficient heat removal; reduced molten salt circulation	Core overheating; material degradation; structural stress; reactor shutdown

Through the structured combination of parameters and guide words, it enabled the identification of specific operational paths leading to unsafe or undesirable states. This makes HAZOP more demanding, but also more useful for understanding process behaviour and for proposing more targeted safeguards or recommendations.

6. Conclusions

This paper aimed to make a preliminary qualitative risk analysis, combining HAZID and HAZOP methodologies, on the introduction of MSR in vessel propulsion systems.

The analysis confirms that the MSR concept offers relevant advantages for marine applications, particularly because of its low-pressure operation, high energy density, thermal efficiency potential and passive safety features. However, the study also highlights important safety challenges, especially those related to molten salt circulation, heat removal, abnormal reactivity conditions, material corrosion, gas management and the reliability of passive drainage systems.

The combined HAZID and HAZOP results, incorporating a maritime propulsion perspective, show a clear hierarchy of node criticality. Nodes 1, 2, 7 and 8 are the most critical, as they directly affect reactor safety and propulsion continuity. Node 6 also presents high criticality due to its radiological implications, while nodes 3, 4 and 5 mainly impact efficiency and performance. Finally, node 9 is associated with progressive effects on long-term system reliability.

The HAZID analysis was effective, since it provided a broad identification of the most relevant hazards. The HAZOP assessment, in turn, provided a more detailed understanding of node-level deviations and of the pathways by which normal operation may evolve into unsafe or undesirable states.

This confirms that the two methods are not competing alternatives, but complementary tools within a coherent qualitative risk assessment strategy.

From a maritime engineering perspective, the combined application of HAZID and HAZOP supports more robust early design thinking for advanced nuclear propulsion systems. The results suggest that particular attention should be given to the primary salt circuit, passive emergency drainage provisions, gas management and chemical conditioning, since these functions are central to both reactor safety and operational reliability.

Future work should refine the present analysis through a more detailed development of each node, the expansion of the HAZOP deviation set, and, where feasible, the progressive integration of semi-quantitative or quantitative techniques

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The role of navigation simulators in developing seafarers' safety competencies and reducing human error in navigation

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Abstract: The safety of navigation in modern maritime transport depends on the level of seafarers' competence and their ability to make the right decisions in complex and stressful navigational situations. Navigation simulators are an important tool in the education and training of seafarers. In accordance with international training standards, they enable the acquisition and practice of various skills in safe and controlled environment. The aim of the paper is to investigate the contribution of navigation simulators to the development of safety-related seafarers' competencies and their impact on reducing the risk of human error in navigation. The paper analyses relevant professional and scientific literature, as well as International Maritime Organization standards, with special emphasis on the STCW Convention and IMO Model Courses. A bibliometric analysis using the VOSviewer software was applied to systematically review the literature, identify thematic research groups and the most significant contributions in the field of navigation simulators. The empirical part of the study is conducted through a survey-based research approach involving maritime students and seafarers. The collected data are analysed using statistical methods with the aim of assessing the perception of the effectiveness of simulation systems in education and training. The research results indicate the positive impact of navigation simulators on the development of navigation and safety competencies of seafarers. The findings confirm the importance of navigation simulators as a key element of the modern system of education and training of seafarers in the function of improving navigation safety and reducing the probability of human error in real-world situations

Keywords: navigation simulators; navigation safety; seafarer training; human error

1. Introduction

Maritime transport is an important element of the global transport system and plays a key role in international trade, with the majority of world trade carried out by sea. Despite significant technological advances in shipbuilding, navigation systems and safety equipment, navigation safety still largely depends on the human factor, i.e., the competencies and professional qualifications of seafarers. Historically, maritime transport has been associated with high risks to human life and property since its inception, and the lack of a standardized system of education and training for seafarers has often resulted in maritime accidents and the loss of ships and lives. Earlier maritime navigation was based mainly on the experiential transfer of knowledge and skills between seafarers, and there was no systematic approach to education or clearly defined safety standards. Nowadays, seafarer training is mostly carried out through various simulators that enable training in navigation procedures, decision-making and responding to exceptional situations in controlled conditions. Also, during seafarers' training on simulators, it is possible to simulate almost all real situations without risk to the crew or the ship, which allows participants to improve their skills and apply theoretical knowledge in a practical environment. The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) prescribes minimum standards of competence and foresees and regulates the use of simulators in the process of training and knowledge assessment (IMO, 2010). The provisions of the Convention and the associated STCW Code define requirements related to the quality, functionality and pedagogical justification of simulators, as well as the conditions under which simulator training can be recognized as part of mandatory training and assessment of competencies. In accordance with IMO guidelines, simulators must faithfully reproduce real operational conditions on board a ship, enable the development of technical and non-

technical skills (such as teamwork, communication and bridge resource management – BRM), and ensure an objective assessment of the achieved competencies. Dewan et al. (2023) point out that the modern maritime sector, due to the increasing degree of automation and technological complexity of ships, requires highly trained officers who develop their practical competencies to a large extent through simulator training. The special importance of the use of simulators stems from the international regulatory framework that defines the standards of education and training of seafarers, as stated by Kim et al. (2023). Karahalil, Lützhöft, and Scanlan (2023) point out that the international standards of the STCW Convention clearly define the competencies that seafarers must demonstrate, with simulators representing an important tool for their assessment in educational institutions. Bokau et al. (2025) emphasize that simulator training allows seafarers to practice high-risk navigation scenarios, such as navigation in restricted waters or complex ship encounters, without the real consequences that such situations could have in a real environment. These findings are further supported by the results reported by Musulin et al. (2025), which indicate the existence of a significant connection between maritime accidents and the level of implementation of safety activities. In addition to testing difficult navigation conditions, Žagar (2025) state that the simulator environment enables the analysis of mental load and emotional reactions during navigation tasks, which contributes to a better understanding of the learning process and development of professional skills in maritime cadets. Numerous studies indicate that simulation training significantly contributes to the development of practical skills, such as decision-making, communication, and teamwork, which are crucial for navigational safety. Scientific literature emphasizes the need to integrate technical and non-technical competencies into the seafarer training system. Traditional educational models have often focused primarily on technical knowledge, while cognitive and social skills, such as crew resource management and situational awareness, have been less represented. However, research shows that deficiencies in these areas are often the key cause of crew errors and maritime accidents. Therefore, modern approaches to seafarer education increasingly emphasize a competency-based approach that integrates technical knowledge, practical skills and non-technical abilities into a single system of professional development. Despite the existence of international standards and a developed education system, the maritime industry is facing numerous new challenges, such as the development of digital technologies, automation of ship systems, autonomous ships and changes in the organization of work on ships, which require continuous adaptation of the seafarer training system (Muczyński et al., 2025). In this context, some literature indicates the need to modernize.

2. Materials and methods

The methodological approach used to analyze the role of navigation simulators in developing seafarers' safety competencies and reducing human error in navigation employed various methods. The PRISMA method (Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines were used to ensure a systematic and transparent review of the scientific literature by searching, selecting, and analyzing relevant scientific papers (Liberati et al., 2009). Using the PRISMA approach, scientific works dealing with the application of navigation simulators, including technologies such as advanced simulation systems in seafarer training, were identified and analyzed. The research process included the collection of data from relevant scientific databases, the selection of them according to defined criteria, and content analysis. The selection of these databases was based on their broad coverage of the scientific literature and their high reputation in the academic community. A total of 1729 studies were identified, as shown in Figure 1. In the Scopus database, 5 papers were found, in Web of Science (WoS), 55 papers were found, while in the Google Scholar database, 993 papers were found, and in OpenAlex, 676 scientific papers. The following keywords were used to identify relevant studies: “navigation simulators”, “seafarer training”, “human error”, “navigation safety”. The keywords were chosen using the research objectives and scientific papers that analyze the role of navigation simulators in developing safety competencies of seafarers and their contribution to reducing human errors in navigation. VOSviewer software was used for bibliometric analysis and visualization of the relationship between keywords and research trends. After limiting the search to the period 2010-2026 and removing duplicates, the final number of scientific papers was 178.

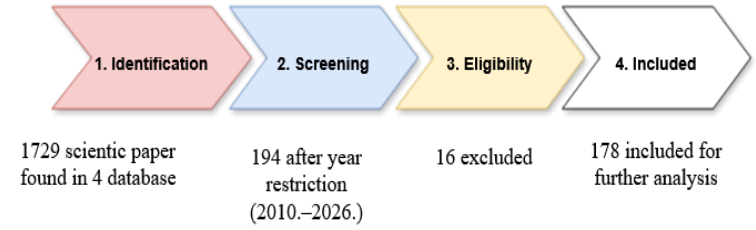


Figure 1. PRISMA 2020 analysis flow diagram for new systematic reviews, including database and other source searches (PRISMA, 2026).

The survey method was used to conduct the empirical part of the research, which involved students from maritime faculties and seafarers in different ship classes in various officer positions. The study involved 49 respondents, who were divided into two groups: students of maritime faculties and active seafarers. The survey results were analyzed using basic statistical methods, and the results serve as an empirical supplement to the review of scientific literature.

3. Results and Discussion

3.1. Literature analysis using PRISMA and VOSviewer

Through the analysis of scientific literature, the main research trends concerning the use of navigation simulators in maritime education have been identified. After the selection and filtering of the literature, including the period from 2010 to 2026 and the removal of duplicate scientific papers, a final set of 178 scientific papers was obtained, shown in Table 1. The analysis of this set provided a detailed overview of research on navigation simulators, their role in the development of seafarers' safety competencies, and their contribution to the reduction of human errors in navigation. The results of the bibliometric analysis also highlight key trends and connections between terms, which can serve as a basis for further research and improvement of seafarers' training programs. The analysis shows that the field of research on navigation simulators and seafarers' safety competencies remains very relevant, with a clear trend of growing interest in the scientific community. These results show that seafarer education, navigation simulators and navigation safety are what is often called a "hot topic" in science. The research trend is inevitable, the link is shown in Figure 2 using the VOS viewer software (VOSviewer, 2023). VOSviewer software has enabled the visualization of keywords, revealing a strong connection between terms like STCW, maritime training, human factor, instructor, education, student, navigator, skill, risk and accident.

Table 1. Distribution of scientific papers identified and included per database in the literature retrieval process. Source: Own research.

Scientific Database	Number of Identified Papers	Number of Selected Papers
Web of Science (WoS)	55	43
Scopus	5	5
Google Scholar	993	83
OpenAlex	676	47
Total	1729	178

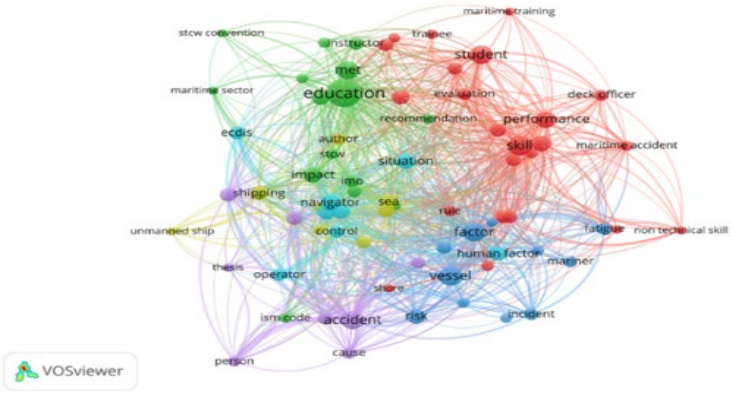


Figure 2. Overlay Visualisation of top keywords used in the articles (VOSviewer, 2023).

3.2. Survey conducted by students vs. seafarers

The aim of the survey was to collect data on their perception and experience of using navigation simulators during education and professional training. Special emphasis was placed on assessing the role of simulators in developing navigation and safety competencies of seafarers, and on their potential contribution to reducing human error in navigation. They provide additional insight into the actual application and importance of simulators in maritime education and practice. The survey for the conducted research was attended by 49 respondents, of which 20 were students of maritime faculties and 29 were active seafarers, as shown in Table 2. According to the age structure, 3 students belong to the group from 18 to 21 years, while the majority, 17 of them, are in the age group from 22 to 25 years. According to the year of study, 12 respondents are in the third year of university, and 8 respondents are in the fourth year. All students who participated in the research had experience working on a simulator and participated in simulator training as part of their education. The second group, active seafarers, consists of 29 respondents. The age structure shows a wider age range: one respondent belongs to the group from 18 to 21 years, 13 respondents are between 26 and 35 years, 8 respondents are between 36 and 45 years and 7 respondents belong to the age group from 46 to 55 years. According to their completed education, 13 respondents completed a secondary maritime school, and 15 respondents have completed a maritime faculty, one stated another type of education. Considering the rank they hold in their workplaces, among the respondents there were: 9 ship commanders, 5 first officers, 12 second officers, and 3 third officers. According to sailing experience, 2 respondents have less than a year of experience, 3 respondents between 4 and 6 years, 11 respondents between 7 and 10 years, while 13 respondents have more than 10 years of work experience on board. Table 2 also shows the types of ships they work on.

Table 2. Structure of respondents by year of study, sailing experience and type of ship. Source: Own research.

Group	Category	Division	Number	Percentage (%)
Students (N=20)	Year of study	3rd year	12	60,0
		4th year	8	40,0
Seafarers (N=29)	Experience	< 1 year	2	6,9
		4 – 6 years	3	10,3
		7 – 10 years	11	37,9
		> 10 years	13	44,8
	Type of ship	Passenger ship (cruiser)	9	31,0
		LNG/LPG tanker	3	10,3
		Oil/chemical tanker	3	10,3

Group	Category	Division	Number	Percentage (%)
		Military ship	4	13,8
		Other	10	34,5

Note: The category “Other” includes individual responses (container ship, cargo ship, speedboat, heavy lift ship, multipurpose ship, offshore ship, port tug, supply ship, tugboat and wind turbine installation ship).

Figure 3 shows students’ assessment of the impact of simulator training on their professional readiness and the development of independent navigation competencies. When it comes to increasing independence in performing navigation tasks, the majority of students (12) believe they are quite independent in performing future tasks on the navigation bridge, while 6 respondents gave the highest rating, that is, they feel completely independent. In terms of confidence in their own navigation skills, the results are also positive. The largest number of students (17) rated the contribution of the navigation simulator very highly, while one student gave the highest rating, and two students believed that the simulator raised their confidence to a moderate level. The average score of 3.95 shows that the simulator significantly contributes to the feeling of certainty in one's own abilities. When it comes to preparedness for dealing with crisis situations, the largest number of respondents (12) believe they are very well prepared for crisis situations, while eight students chose a medium level and believe that a little more practice would be beneficial. The average rating is 3.60. In the assessment of overall preparedness for future navigation, as many as 17 students selected level 4, meaning they feel very ready for future navigation, while two students consider themselves at a medium level of readiness, and one feels unprepared for future challenges. Overall, the results show that students perceive the simulator as an important element in the transition from theoretical education to practice. Although assessments vary depending on specific competencies, high ratings prevail in all segments.

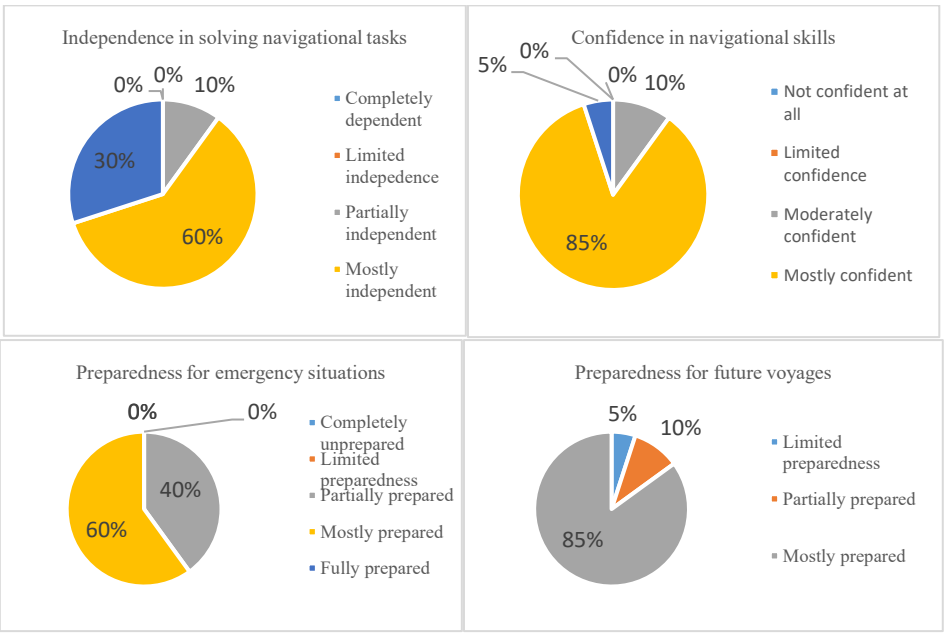


Figure 1. Assessment of the simulator’s contribution to the development of students’ professional readiness. Source: Own research.

Unlike the student group, seafarers were asked additional questions focused on their actual professional experience and the application of knowledge acquired through simulator training in real navigational conditions. These questions addressed the assessment of the simulator’s contribution to overall navigation safety, its impact on reducing the likelihood of human error, the application of simulator-based knowledge in real navigational situations, and the effectiveness of the simulator in handling specific situations at sea. These questions were intended exclusively for seafarers, as they are based on practical experience and real operational conditions. Figure 4 presents the results of four questions aimed at assessing the actual contribution of simulator training

to navigation safety from the perspective of active seafarers. Regarding the overall contribution of the simulator to navigational safety, the majority of respondents (13) believe that the simulator contributes significantly to safety, while 8 consider its contribution to be complete. Seven respondents rate the contribution as moderate, and only one believes that the simulator has no impact. These results indicate that most seafarers recognize the simulator as an important tool for enhancing safety competencies. In terms of reducing the likelihood of human error, 16 respondents believe that the simulator makes a moderate contribution, while 9 indicate a significant contribution. A smaller number of respondents (3) assess the contribution as negligible, and one believes it has no impact. Notably, 21 out of 29 seafarers stated that they had applied the knowledge and skills acquired through simulator training in real navigational situations. This confirms the practical value of simulator training and its strong connection to real-world professional experience. Finally, when assessing the simulator's contribution to handling specific situations at sea, 13 respondents indicated that the simulator was highly helpful, 2 believe it played a decisive role, while 7 rate the contribution as limited. A smaller proportion of respondents' state that the simulator had no impact or that they are unable to assess its contribution.

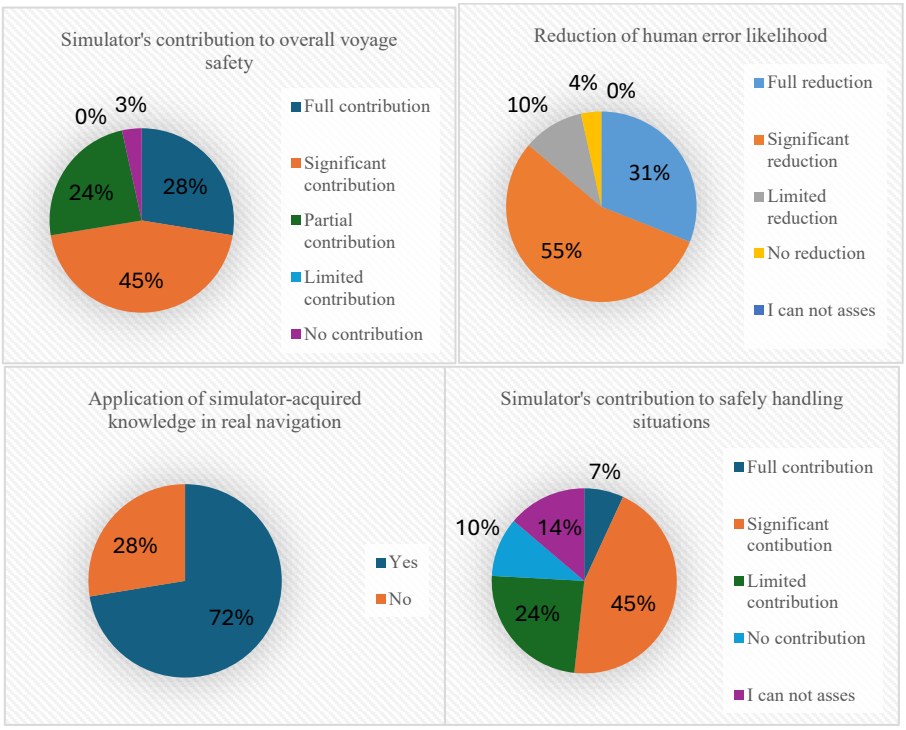


Figure 2. Assessment of seafarers on the impact of simulator training on voyage safety and the application of acquired knowledge in real conditions. Source: Own research

A comparative analysis was also conducted between students and active seafarers with the aim of determining their perception of the connection between theoretical knowledge and practical application in the context of simulator training. The subjects were asked to assess to what extent they believe that the theoretical content covered during education and training is effectively connected to practical situations in navigation. By including both groups in this analysis, it was possible to compare the perspective of future seafarers, who are still in the phase of education, with the experience of professionals who apply theoretical knowledge in real navigation conditions. Accordingly, Figure 5 shows a comparison of the perception of the connection between theoretical knowledge and practical application between students and active seafarers. The results show that students rate the connection between theory and practice very highly. As many as 12 students consider that theory is fully connected with practice, while 8 students chose level 4, meaning they consider the theoretical-practical part very connected. No one chose lower rating levels, and the average value is 4.60. These results indicate that students consider simulator training and theoretical classes to be very effective in preparing for practical navigation situations. On the other hand, seafarers also rate the connection between theory and practice positively, but somewhat more moderately compared to students. The largest number of seafarers (16) chose level 4, while 7 respondents gave the highest rating. Five respondents assessed the connection at a moderate

level, and one believes that theory and practice are connected to a lesser degree. The average rating is 4.00, which still represents a high level of agreement with the statement that theory is closely connected to practical work on the ship.

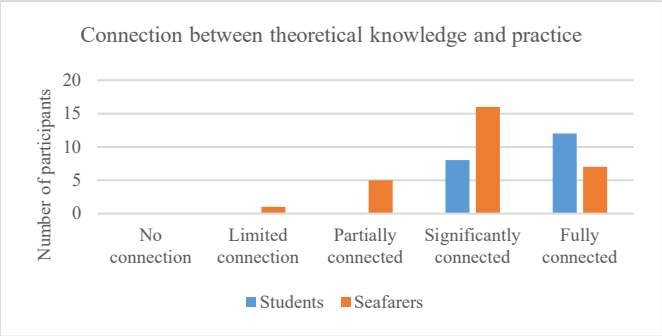


Figure 3. Assessment of students and seafarers on connection between theoretical knowledge and practice. Source: Own research.

At the end of the research, participants were asked to describe the main advantages and disadvantages of simulator training in their own words, providing qualitative insights beyond predefined responses. Students highlighted the possibility of realistically depicting work on a ship and on the bridge as the greatest advantage of the simulator. Several participants stated that the simulator provides an opportunity to get a “feel of the bridge”, “feel of working on a ship”, and a better “sense of the ship and the bridge”. They also emphasized that the simulator helps in connecting theory and practice and allows for a better understanding of theoretical content through concrete situations. The perception of the simulator as a tool that shows real navigational situations and allows testing navigation under conditions that are most similar to actual ship conditions stands out. Students highlighted its role in developing independence on the bridge and preparing for future professional work, while seafarers emphasized its ability to apply theoretical knowledge in practice without risk. Several respondents emphasized that the simulator allows practicing without risk to people and ships and provides an opportunity to train for emergency situations and crisis maneuvers. The simulation of real situations on a ship, gaining experience in conditions similar to actual navigation, and the possibility of practicing maneuvering and responding in critical situations are often mentioned. Seafarers also highlighted the importance of working with navigation equipment, such as RADAR and ECDIS, and becoming familiar with the equipment that will be used in future work. Some respondents stated that the simulator helps in avoiding collisions, practicing the application of COLREG rules, and developing safety awareness. Along with numerous advantages, students also pointed out certain disadvantages of simulator training. The most commonly mentioned drawback relates to insufficient realism compared to actual conditions at sea. Several respondents noted that the simulator "is not realistic enough," that "it is not realistic in terms of sea conditions", and that it "should be more modern" or include more real-life situations. A lack of unpredictable and complex situations characteristic of real navigation is also mentioned. Seafarers also highlighted a number of limitations of simulator training, with most remarks referring to the difference between the controlled simulation environment and real, often unpredictable, conditions at sea. It was emphasized that simulator exercises often remain highly controlled and cannot fully replicate emergencies and stressful situations. Some respondents stated that the simulator "cannot replicate real ship conditions", that it lacks the feeling of real danger, and that the movements of the ship, rolling, and other physical effects of sailing cannot be felt. Some seafarers also pointed out technical limitations, such as an insufficient number of simulators, incompatibility of equipment with actual ship equipment, outdated systems, or insufficient digital infrastructure. It was also mentioned that participants on the simulator are often more relaxed than in real situations, and that sometimes the simulator can give the impression of a "game," which diminishes the sense of responsibility present in actual work. In addition to advantages and disadvantages, all students believe that the simulator should play a greater role in the education and training of seafarers. A similar view is expressed by the vast majority of active seafarers, who also support the expansion of simulator-based training in professional qualifications.

4. Conclusion

The literature review confirms that navigation simulators represent a highly relevant and continuously developing research area. There has been a visible increase in scientific papers in recent years. Thematic connections were noted, particularly those related to STCW standards, human factors and maritime training, highlighting the central role of simulators in improving safety competencies and reducing human error in navigation. Students and seafarers recognize simulators as an extremely important tool in modern maritime education. The results of the quantitative analysis indicate a high level of satisfaction with the simulator's contribution to the development of navigation skills, understanding of COLREG rules, managing emergency situations and working with navigation equipment such as RADAR and ECDIS systems, as well as with the rest of its features that improve skills at sea. A large number of seafarers confirmed that they have applied the knowledge gained on the simulator in real navigation situations, which confirms its concrete and practical value. Both groups strongly support the idea that simulator training should have an even more significant and systematic role in maritime education and training. The qualitative results identified limitations of simulator training, including insufficient realism, limited sea experience, unpredictability, and technical obsolescence. These findings highlight the need for continuous simulator development and adaptation of training programs. Feedback from students and seafarers should be the basis for further improvement of the system, and the findings provide a deeper insight into the development of navigation simulator research, their impact on navigation safety and the potential for further improvement of seafarer training. This study is limited by the relatively small sample size and the use of descriptive statistics. Future research should include larger samples and more advanced statistical analyses to improve the generalizability of the findings.. They also emphasize the need for continuous research and improvement of training programs in order to further reduce human error and increase safety at sea.

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Maritime Trainees' Responses to Unexpected Navigation and Technical Failures: A Simulator-Based Eye-Tracking Study

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Abstract: Human factors are widely cited as the primary cause of maritime accidents. Causes may vary from fatigue, stress, high cognitive load, pressures, workload, decision-making errors to many more influenced factors (Maternová, 2019), (Russo et al., 2022) leading to reduced situational awareness which is identified as key risk factor contributing navigational errors and incidents (Vojković et al., 2021). Assessing cognitive focus and stress responses during navigation remains a challenging task, as these factors are highly individual and influenced by variables such as experience, training, knowledge, and innate predispositions.

In this paper the eye-tracking-based stress responses of maritime trainees during simulator-based exercises are presented, with a focus on reactions to technical and navigational errors. The paper presents the development of a simple and effective stress level indicator (SLI - Stress Level Indicator) that combines several oculomotors and pupillometric parameters, and its application to heterogeneous groups of seafarers in a simulated crisis scenario.

Keywords: human factors; situational awareness; eye-tracking

1. Introduction

Maritime transport is one of the most demanding and responsible areas of human activity, in which human error and stress are recognized as key risk factors. Despite the increasing automation and digitalization of navigation and control systems, the human factor still plays a key role in decision-making, especially in emergency (crisis) situations. Therefore, understanding the cognitive processes and stress of operators in real or simulated conditions is of paramount importance for improving navigation safety (Hetherington et al., 2006; Djukanović et al., 2020).

Eye-tracking technology has been increasingly used in recent years for objective monitoring of cognitive load and stress (Pupil Labs), since changes in eye movements (eg in fixations, movement dynamics, pupil diameter) reflect changes in the observer's mental state (Holmqvist et al., 2011).

An automated analysis pipeline was developed to transform raw gaze data into interpretable behavioral scores. In order to better understand the reaction of trainees and improve simulation exercise scenarios on a nautical simulator, and ultimately better prepare future officers for navigation, research was conducted on a nautical simulator that connects nautical knowledge and reaction to unwanted situations during navigation. The aim of the research is to examine how participants perceive, process, and respond to unexpected malfunctions or deviations from GPS errors, AIS errors, and complex maritime navigation environments, using objective measures of visual attention and cognitive load.

This study builds on existing research and it present preliminary results to better understanding how maritime experts and trainees perform during emergencies. We expect that experienced mariners will use their vision more efficiently. They should spot problems faster, switch their gaze between important screens (like ECDIS and RADAR) in a more predictable order, and return to normal operations more quickly after an incident. In contrast, novice trainees will likely show signs of higher workload and stress. Their gaze might jump erratically between screens, stay too long on non-critical areas, or become unfocused, and they may take longer to recover their focus after a surprise event. A key goal is to link these visual patterns to the body's stress

response. We hypothesize that calm, efficient eye movements, reflect lower stress levels, while frantic, scattered looking will, indicate higher stress levels providing an objective measure of panic.

The research was conducted using a maritime navigation simulator combined with eye-tracking glasses to monitor eye movements (Petrović et al., 2025; Win et al.,2026) Eye tracking enabled the analysis of visual attention patterns during night navigation in high density traffic, including fixations and reaction time to potential collision situations, while eye-tracking derived indicators served as proxies for stress levels and cognitive strain. During the simulation sessions, deliberate technical and navigational errors were introduced to evaluate detection speed, decision making strategies, and subsequent behavioral and physiological changes.

The paper describes the methodology for data collection and processing, defines the SLI indicator, and then presents and analyzes the results obtained. The final section provides main conclusions and guidelines for further research.

2. Methodology

The research methodology is based on the analysis of the respondents' behavior during a simulated crisis scenario. Using eye-tracking technology, data on eye movements (fixations, pupil diameter, gaze shift dynamics) were collected, which were then processed in several steps to enable the calculation of the Stress Level Indicator (SLI).

2.1. Data preparation and processing

For the purposes of this research, a single-blind crisis scenario was developed within a maritime simulator. Participants with varying levels of maritime experience took part in the testing, while their eye movements were recorded using Pupil Core eye-tracking glasses. The output data were processed through multiple stages in order to prepare them for the calculation of cognitive workload indicators.

2.1.1. Preprocessing of Raw Data

The raw data (fixations, gaze positions, pupil diameter, and blinks) were temporally aligned, while blink intervals and low-confidence samples were removed from further analysis (Holmqvist et al., 2011). Fixations were subsequently validated: only those located within the boundaries of the predefined areas of interest (including ECDIS displays, radar screens, external visualizations, and the control console) and within the normalized coordinate range (0,1) were retained (Henderson, 2017).

2.1.2. Calculation of variables

Based on the validated fixations, the following parameters were calculated: the duration of each fixation (ms), the duration and amplitude between two consecutive fixations, and the rate of gaze position change (defined as the ratio between amplitude and duration).

2.1.3. Participant Characteristic and Time Segments

For each participant, demographic data were recorded, including age, rank, and seagoing experience. The temporal course of the exercise was divided into three periods: (1) the period prior to the onset of the crisis situation, (2) the period immediately following the onset of the crisis, and (3) the remaining part of the exercise until its completion.

2.1.4. Visualization of the Spatial Distribution of Attention

Figure 1. presents the temporal distribution of fixations across the surfaces. Figure 2. shows, for each surface, the gaze density (heatmap), the position of the central point (centroid), and the ellipse describing the spatial dispersion of the samples. The shape and size of the ellipse indicate the participant’s level of focus: a smaller ellipse suggests focused attention, whereas a larger ellipse indicates more extensive visual scanning. The displayed coverage percentage represents the proportion of the surface that was visually covered by the participant’s gaze.

These visual representations serve as an initial, exploratory phase of the analysis, on the basis of which quantitative indicators of stress-related workload were defined in the subsequent step.

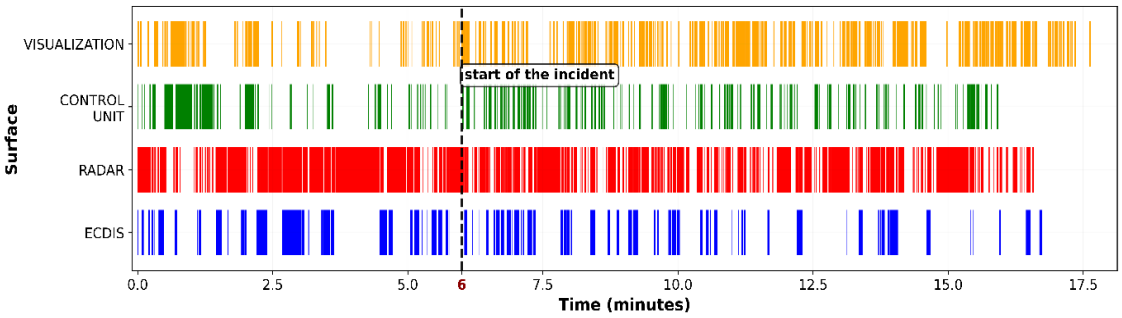


Figure 1. Temporal distribution of participant fixations across the observed surfaces

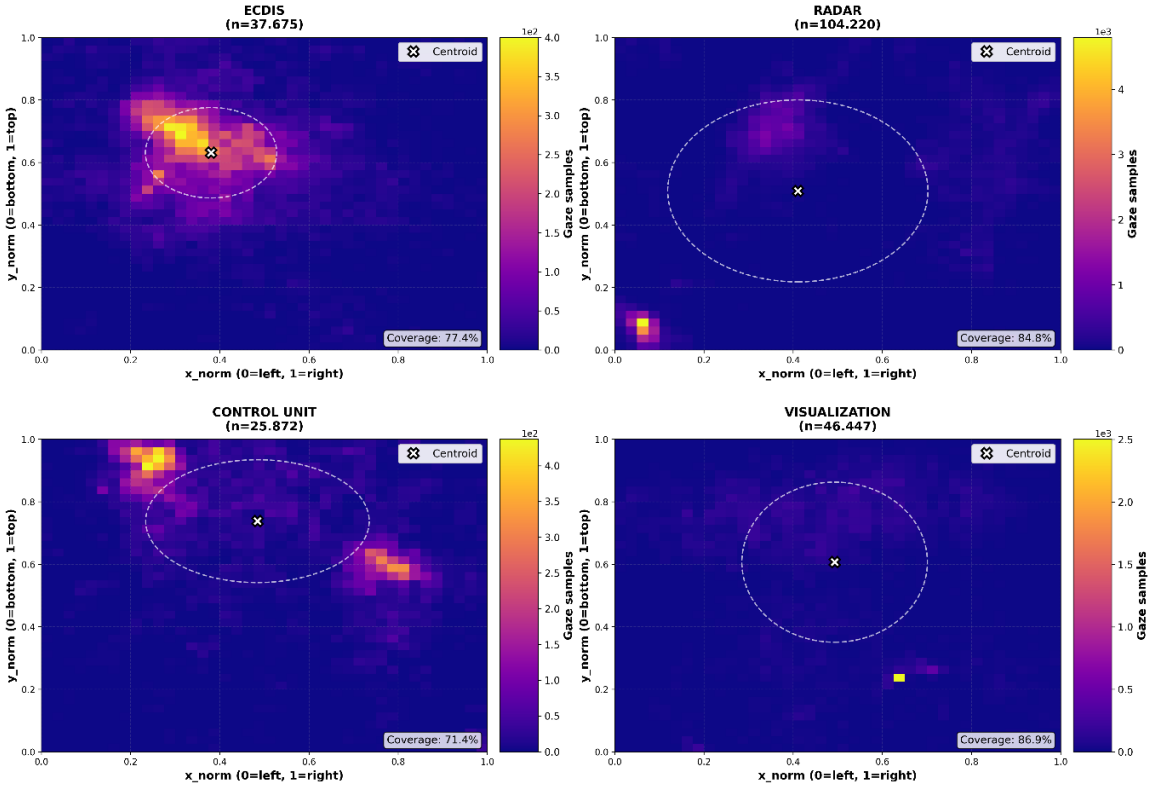


Figure 2. Gaze heatmap graph across surfaces with displayed centroids

2.2. Stress Level Indicator

To quantify stress levels, an index was developed that integrates three complementary types of parameters: (i) pupil diameter as a physiological indicator of effort, (ii) spatial dispersion of gaze as an indicator of attentional focus, and (iii) eye movement dynamics (frequency and speed of gaze shifts) as an indicator of visual search activity.

For each participant, within each of the three defined periods (the exercise phase before the crisis, the exercise phase immediately after the crisis, and the remaining part of the exercise) and for each observed surface, individual values were calculated for each of the aforementioned parameters. The values were then normalized to a common scale to enable their combination. The final Stress Level Indicator was calculated as a weighted sum of the normalized components. The weights (pupil diameter: 0.4, gaze dispersion: 0.3, gaze shift dynamics: 0.3) were determined through expert assessment (consensus of three subject-matter experts) and subsequently

validated using Principal Component Analysis (PCA) on the full dataset, which confirmed the structural consistency of the chosen weights.

The indicator values range from 1 to 10, with higher values indicating higher stress levels. Based on the distribution of values within the sample, the following thresholds were defined: values ≤ 4 indicate a low level of stress (resilience), while values ≥ 9 indicate a very high level of stress (severe stress). These thresholds correspond to the 10th and 90th percentiles of the empirical distribution of SLI values across the full sample. This ensures that the thresholds are data-driven and reflect the natural variation in stress levels within the tested population, rather than arbitrary cut-offs. The minimum recorded SLI value in the entire sample was 4 (see Table 1), confirming that the scale captures low-stress states. Given the nature of the simulated crisis scenario (GPS and AIS failures, potential collision situations), it is reasonable to assume that all participants experienced at least some level of stress, which is reflected in the fact that no participant recorded a SLI value below 4. Thus, the SLI scale successfully captured both low-level and high-level stress responses. These thresholds were used to classify participants in the analysis presented in Figures 3., 4., and 5.

3. Results and Discussion

To examine the relationship between different factors (rank, age, and seagoing experience) and stress levels, descriptive SLI values were calculated for each of the observed groups. The results are presented in Table 1, while the distributions of values across groups are shown in Figures 3.,4. and 5.

Table 1. Descriptive statistic of SLI by demographic groups

Group	N	Mean SLI	Median SLI	SD	Min	Max
Rank						
Master over 3000 BRT	6	7,8	8,0	0,4	7	8
Master up to 3000 BRT	1	10,0	10,0	–	10	10
Student	17	8,0	8,0	1,7	4	10
2nd off	21	8,1	8,0	1,6	4	10
High school	17	8,2	8,0	1,3	4	10
3rd off	1	8,0	8,0	–	8	8
Age						
< 25	29	8,2	8,0	1,4	4	10
25 – 50	31	8,0	8,0	1,6	4	10
> 50	3	8,7	8,0	1,2	8	10
Seagoing Experience (age)						
1 – 5	2	6,0	6,0	2,8	4	8
6 – 10	11	8,2	8,0	1,7	4	10
11 – 20	13	8,2	8,0	0,8	7	10
> 20	4	8,5	8,0	1,0	8	10

Note: SLI ranges from 1 to 10, where higher values indicate higher stress levels. The resilience threshold is defined as ≤ 4, while the severe stress threshold is defined as ≥ 9.

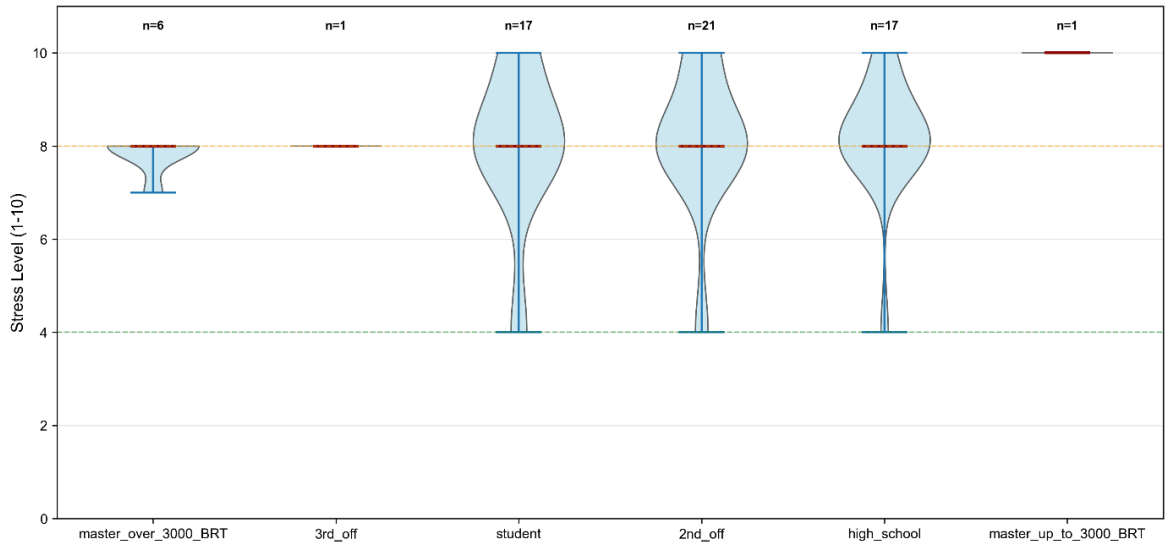


Figure 3. Stress level distribution according to participants' rank

Figure 3. shows the distribution of SLI values according to participants' rank. The lowest average stress level (7.8) is observed in the Master over 3000 GT group, while the Master up to 3000 GT group (consisting of only one participant) records the maximum value of 10. The 3rd Officer group also consists of a single participant (n=1). Due to the extremely small sample size (n=1), this finding should be interpreted with caution and is considered preliminary. Students and Second Officers show the greatest variability (4–10), indicating the presence of both highly resilient and highly vulnerable individuals within these groups. Rank alone is not a sufficient predictor of stress; individual differences in attentional patterns need to be further analyzed.

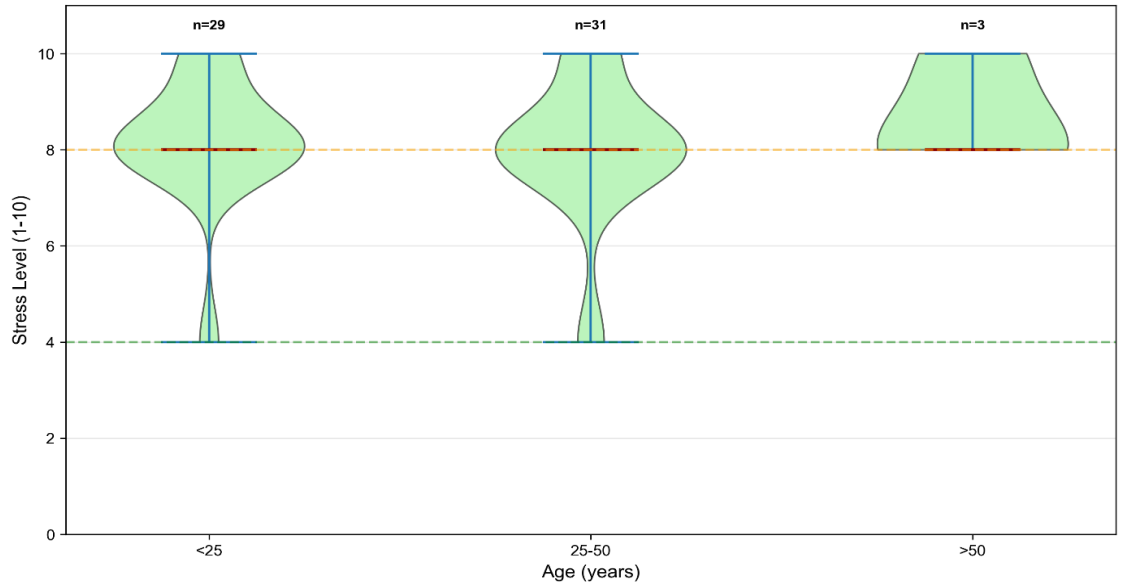


Figure 4. Stress level distribution according to participants' age

Figure 4. shows the distribution of SLI values according to participants' age. The lowest average stress level is observed in the 25-50 age group (8.0), while participants over 50 years exhibit the highest average value (8.7). Respondents older than 50 are exclusively within the range of 8-10, with none reaching the resilience threshold (≤ 4). This finding suggests that although experience increases with age, cognitive flexibility may decline, making older participants more susceptible to higher stress levels. Participants under 25 show a similar average (8.2) but greater variability, including some of the most resilient individuals (level 4).

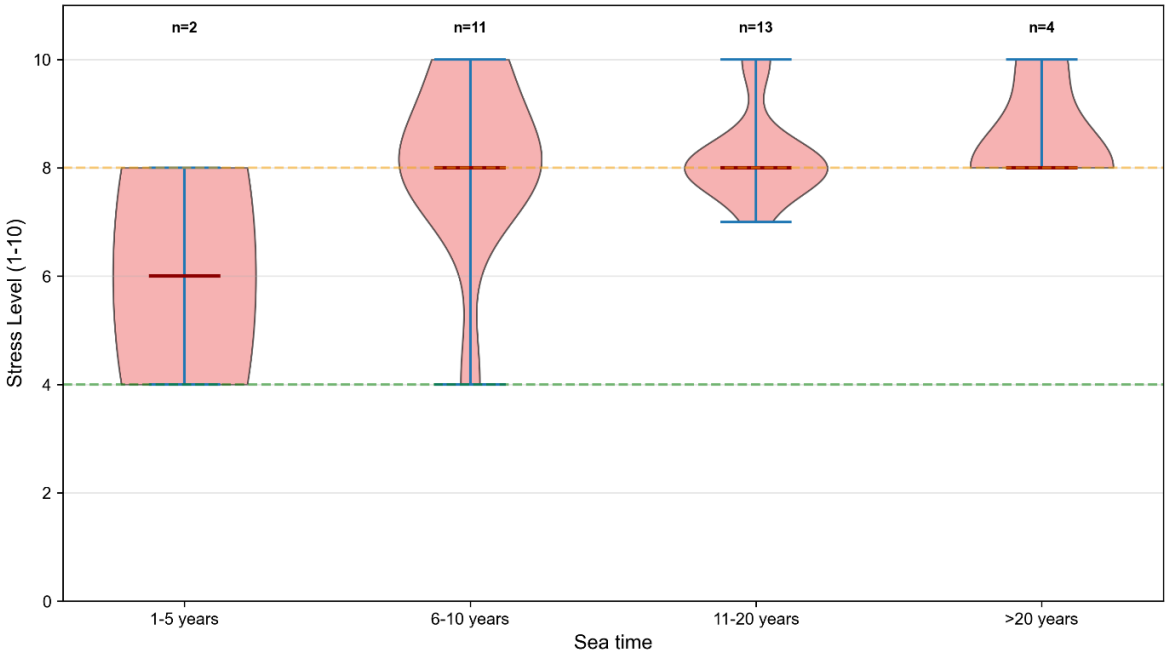


Figure 5. Stress level distribution according to seagoing experience (age)

Figure 5. shows the distribution of SLI values according to seagoing experience. The lowest average stress level is observed in the group with 1-5 years of experience (6.0), although the sample size is very small (n = 2), so conclusions should be interpreted with caution. The highest average stress level is found in the group with more than 20 years of experience (8.5), where all participants fall within the range of 8-10. This finding suggests that long-term experience does not necessarily protect against stress; on the contrary, it may be associated with more rigid attentional patterns and reduced cognitive flexibility. The 6-10- and 11-20-years groups show nearly identical mean values (8.2), but the former exhibits considerably greater variability (4–10), indicating that this group contains both the most resilient and the most vulnerable participants.

Taken together, these findings are consistent with the hypotheses outlined in the Introduction: experienced mariners (e.g., Masters over 3000 GT) exhibit lower and more stable SLI values, while novices (students and Second Officers) show greater variability, reflecting the expected differences in gaze efficiency and stress response. The observed variability within demographic groups confirms that individual attentional patterns are a more important predictor of stress than broad demographic categories alone.

4. Conclusion

This study presents an approach for quantifying operator stress in a maritime simulator using eye-tracking technology. The developed Stress Level Indicator integrates three complementary measures (pupil diameter, spatial gaze dispersion, and eye movement dynamics) into a single numerical value on a 1-10 scale. The results indicate that there is no simple relationship between demographic factors (rank, age, seagoing experience) and stress levels. Although certain groups (e.g., older participants and those with long seagoing experience) on average exhibit higher stress levels, substantial variability is present within each group, ranging from highly resilient to highly vulnerable individuals. This suggests that individual attentional patterns are a more important predictor of stress than broader demographic categories.

The proposed SLI indicator has proven to be a sensitive and comprehensive tool for assessing stress in simulation environments. From a practical perspective, the SLI could be integrated into simulator-based training as a real-time feedback tool for instructors, enabling identification of trainees exhibiting excessive stress or maladaptive gaze patterns (e.g., panic scanning or cognitive tunnelling). Furthermore, the observed variability within demographic groups implies that individual attentional patterns, rather than rank or experience alone, should guide the development of personalized training interventions. Finally, the SLI could inform the design of adaptive simulation scenarios where the difficulty level is dynamically adjusted based on the trainee's

current cognitive load. Future research will focus on a more detailed analysis of individual visual attention patterns, as well as the application of the developed methodology in other domains.

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Improving IMO SMCP and GMDSS Competence AI-Assisted Maritime English Teaching (at the example of BSMA Study)

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Abstract: Effective communication in Maritime English is a cornerstone of maritime safety, particularly during emergency situations where rapid, clear, and standardized message exchange is essential to protect human life, vessels, and the marine environment (IMO, 2001; STCW, 2011). Within maritime education, Maritime English serves as the linguistic foundation for applying the IMO Standard Marine Communication Phrases (SMCP) and operating within the Global Maritime Distress and Safety System (GMDSS) (IMO, 2001) While GMDSS provides the global technological framework for transmitting distress alerts and coordinating search and rescue operations, SMCP ensures clarity and reduces misunderstandings through internationally standardized phraseology (IMO, 2001; Weintrit & Neumann, 2016).

This study examines the role of AI-assisted tools in enhancing the teaching of maritime emergency communication within the Maritime English classroom. To evaluate the effectiveness of AI-supported instruction, a structured survey was conducted among maritime students to assess their theoretical knowledge, communication confidence, and ability to apply standardized emergency communication procedures in English. The survey measured students' understanding of SMCP and GMDSS message structure, their confidence in emergency communication, and their perceptions of AI-based teaching tools. Scenario-based questions required students to analyze simulated emergency situations and identify the appropriate distress priority (MAYDAY, PAN-PAN, or SECURITE), while also demonstrating correct use of Maritime English by applying IMO SMCP phraseology and proper GMDSS message structure (IMO, 2001; STCW, 2011).

The results suggest that integrating AI into Maritime English education strengthens emergency communication competence, supports instructors through targeted feedback mechanisms, and contributes to the preparation of safer and more digitally competent maritime professionals.

Keywords: maritime communication, emergency response, IMO SMCP, GMDSS, safety at sea

1. Introduction

Ability to communicate effectively serves as a vital element of maritime safety, especially in emergency situations when the exchange of timely and accurate information is essential to protect lives, ships and the marine environment. Maritime English plays an important role in ensuring clear and standardized communication among multinational crews as English is the operational language of international shipping. To reduce the risks of misunderstandings, the International Maritime Organization (IMO) has introduced Standard Maritime Communication Phrases (SMCP), which aim to ensure clarity, conciseness and uniformity in maritime communications (IMO, 2001). At the same time, the Global Maritime Distress and Safety System (GMDSS) provides a technological framework that supports distress calls and coordination of search and rescue efforts worldwide (IMO, 2015). In addition, the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) emphasizes the importance of communication skills, requiring seafarers to demonstrate proficiency in maritime English, especially in safety-related situations (IMO, 2019).

Despite the presence of these standardized frameworks, maritime university students still face difficulties in applying theoretical knowledge of SMCP and GMDSS to real-world communication situations as shown by both academic research and practical experience. Common challenges include limited experience in real-world emergencies, insufficient practice in communicating structured messages and a lack of confidence in using standardized phraseology under stress. While traditional teaching methods are effective in conveying theoretical knowledge, they may not fully support the development of practical communication skills required in a dynamic maritime environment.

Advancement of digital technologies, especially artificial intelligence (AI), are creating new opportunities to improve teaching of Maritime English. AI-based tools can offer interactive, scenario-based learning environments, provide immediate feedback and tailor instruction to the needs of individual learners. These capabilities are particularly valuable for developing communication skills in emergency situations, where both linguistic accuracy and procedural correctness are critical. Therefore, integrating AI into Maritime English teaching is a promising way to bridge the gap between theoretical knowledge and its practical application.

2. Literature Review

2.1 Maritime Communication Standards, SMCP and GMDSS in Maritime Safety

Major importance of the language in the area of maritime safety has been systematically illustrated in scientific articles. While analyzing human factors in the maritime accidents published in the Journal of Safety Research, communication was identified as one of major causes of maritime accidents, together with stress, fatigue and inadequate situational awareness by the authors Hetherington, Flin and Mearns (2006). Analysis of twenty studies by the afore-mentioned authors found that the cases of inadequate communication represent a structural weakness during maritime operation rather than incidental concern. This finding was supported by Gabedava and Hu (2025) in the WMU Journal of Maritime Affairs on the basis of linguistic analysis of Voyage Data Recorder (VDR) logs from 429 maritime accidents and near-miss incidents in the period of 2018-2023, showing that speech act uncertainties and lexical inaccuracy contributed to 37.77 percent of accidents and 62.33 percent of near-miss situations. Their study also supported advance SMPC learning and integration of linguistically informed procedures within GMDSS operational framework rather than offering Maritime English as a separate language course.

Adopted in November 2021 by the 22nd IMO Assembly through Resolution A.918 (22), SMCP replaced an earlier Standard Maritime Navigational Vocabulary of 1977, which was developed as a simplified standardized safety language for spoken communication on board, between the ships and ports (IMO, 2001). According to Kovaňvić (2022) who examined Maritime English in the European Journal of Social and Educational Research, SMCP is a restricted language with an intentionally simplified register of English in which standard structures have more functional rather than stylistic usage, reducing the risk of verbal exchange of information critical to safety. Additionally, this viewpoint was supported by Farjami (2024) by declaring that lack of current regulatory framework to train Maritime English communication skills continues to be a major barrier to standardization, due to which it is nearly impossible to effectively teach SMCP only via traditional language instruction. Under STCW, the officers in charge of navigational watch on the vessels with a gross tonnage of 5000 or more were asked to be competent in SMCP, integrating the standard into the global training framework (STCW, 2011; IMO, 2019).

The above-mentioned short literature review indicates at a clear separation of function with SMPC selecting what is said and how it is understood by nearby vessel or Rescue Coordination Center whereas GMDSS establishes technical means and procedures at which distress communication must be initiated. Present study which investigates whether AI-assisted instruction may more successfully create an integrated communication competence that is required by GMDSS operation and whether SMCP training aims to produced, is theoretically grounded with these findings.

2.2. Challenges in Maritime English Learning and Emergency Communication Competence

Maritime English is serves as a specialized branch of English for Specific Purposes, which is developed in order to meet operational communication needs existing in the global maritime field. Since English is a

common language at sea due to multicultural composition of the crew therefore communicative competence in English is crucial for safe navigation. Since poor communication has been considered as a significant factor in maritime accidents study identified that ME is not only a language requirement but also safety critical issue (Trenkner, 2010; IMO, 2001). With this in mind, communication accidents are often categorized as human errors, still remaining one of the main reasons for maritime disaster (Ziarati et al., 2014).

The multilingual and multicultural environment in which seafarers work represents of the main obstacles to learning Maritime English. Because crew members often come from different linguistic backgrounds, there are differences in spoken language norms and levels of English proficiency. These differences can lead to miscommunication, especially under stressful conditions where both accuracy and clarity are crucial. Communication is becoming even more difficult as the result of cultural variations, since they influence the way the messages are transmitted or understood via ambiguity, hierarchy and various interpretations of authority (Pritchard, 2011).

The disparity between Maritime English Instruction and needs of real-world communication is another vivid problem which is mentioned in the literature. The Communicative reality onboard the vessel is not reflected enough in many academic programs, which are mostly based on textbook-based instruction and general language assignment. Based on undertaken needs analysis, seafarers often have not enough linguistic competence to realize bridge communication, respond to distress call and coordination with port authorities (Bocanegra-Valle, 2012). This gap implies that existing instruction often fail to proving students the skills to communicate under real-life situations, in particular emergency conditions.

Another challenge to overcome lies in unsystematic usage of already established frameworks. Application of Standard Maritime Communication Phrases (SMCP) introduced by the International Maritime Organization (IMO) ensures clarity and minimizes uncertainty in various ways in different training programs and institutions. Correspondingly, were unable to reach the degree of uniformity necessary for effective global communication. Program structure and assessment procedures are further complicated via prolonged discussion in order to strike gap between proficiency in General English and skills for specialized maritime communication (Trenkner, 2009).

The lexical uncertainty and inaccuracy of maritime English represent significant language barriers. In safety-critical situations, even minor misunderstandings can have serious consequences. Studies show that the likelihood of misinterpretation is significantly increased by ambiguous language, non-standard phraseology, and deviations from SMCP, especially under stressful and time-critical conditions (Kovačević, M., 2022). This highlights the importance of conciseness, clarity, and adherence to accepted idioms when teaching Maritime English.

One particularly important aspect of maritime English competence is communication skills in emergency situations. In times of stress, uncertainty and time constraints, seafarers must communicate in a prompt, accurate and effective manner. In such situations, poor language skills can lead to delayed reactions, improper actions and escalation of events. Study has demonstrated a clear connection between Language Competence and ability to coordinate and carry out team work in emergency conditions (Ziarati et al., 2014). This highlights at the ability to communicate in competent manner under emergency conditions to incorporate the ability to interact in a strategic and dynamic way.

Effective emergency communication requires a comprehensive set of skills, including linguistic, operational, sociolinguistic and strategic skills. Sailors must be able to follow established communication procedures, use accurate terminology, and adapt language to different interlocutors and rapidly changing circumstances. Strategic competence - the ability to verify, clarify, and resolve communication gaps - is particularly important to avoid misunderstandings. The integration of knowledge, skills and contextual awareness is emphasized in more general models of communicative competence in English for Specific Purposes that are consistent with these competencies (Canale & Swain, 1980).

Pedagogical shortcomings of traditional teaching approaches aimed at developing successful maritime English proficiency are highlighted in the literature. Without practical application in the classroom, students may be inadequately prepared for the complexities of real-world communication. Because scenario- and

simulation-based teaching allows students to get involved in real-life communication situations and practice responding to emergencies, it is becoming increasingly popular. These methods improve situational awareness, decision-making and language skills (Bocanegra-Valle, 2012).

Technological advances have opened up new opportunities for teaching Maritime English. Digital simulations, virtual reality and AI-powered learning systems offer interactive and immersive learning opportunities. By providing students with the opportunity to practice communication in a safe yet authentic environment, these technologies help to bridge the gap between theory and practice. Study shows that technology-based learning can significantly improve confidence and language skills in emergency communication situations (Ziarat et al., 2014).

In conclusion, the literature clearly shows that emergency communication skills and maritime English are essential elements of maritime safety. Despite the availability of standardized methodologies such as the SMCP, significant challenges remain, including linguistic diversity, gaps in training and practice and a lack of focus on real-world communication. Addressing these challenges requires a shift to competency-based, context-based, and digital technology-based training methods. Maritime education can better prepare seafarers for communication challenges they face, especially in emergencies, by aligning training with real-world conditions and emphasizing clarity, standardization and cross-cultural sensitivity.

2.3 Artificial Intelligence in Maritime English Education and Simulation-Based Learning

With the reference to the growing demand for more effective, flexible and context-sensitive language instruction in the maritime industry, artificial intelligence (AI) is increasingly being integrated into maritime English teaching. Maritime English is a specific area of English for Specific Purposes (ESP) that requires both linguistic competence and accurate communication in operational and safety-critical situations. AI-powered learning environments that can adapt lessons and provide instant feedback are becoming increasingly popular since traditional teaching methods often fail to meet these complex demands. Research shows that by adapting to individual proficiency levels and learning needs, AI-powered tools, such as intelligent tutoring systems and natural language processing applications, can increase student engagement and promote the development of communicative competence (Zawaki-Richter et al., 2019).

The ability of AI to reproduce real-world communication situations is a significant advantage for maritime English instruction. Learners can practice standardized phraseology, such as the IMO Standard Maritime Communication Phrases (SMCP), in interactive environments that simulate real-world maritime communication using speech recognition technology and conversational agents. These tools allow for repeated practice and error correction in a low-risk environment, which is particularly important for learning the accurate and understandable terminology required for maritime operations (IMO, 2001). AI systems can also track learner progress over time, providing data-driven insights that help teachers and learners identify areas for improvement.

The increasing use of simulation-based learning in Maritime English instruction is closely related to integration of artificial intelligence. Virtual reality platforms and bridge simulators serve as examples of simulation systems that offer interactive experiences simulating shipboard conditions and emergency situations. These systems integrate language, operational and decision-making skills, allowing learners to apply language skills in context. Studies show that simulation-based learning improves situational awareness, teamwork and language proficiency, which are important in the maritime environment (Bocanegra-Valle, 2012). Simulations help to bridge the gap between theory-based learning and real-world communication needs by exposing students to real-world situations.

Communicative competence combines artificial intelligence-based learning and simulation. Artificial intelligence-based simulations allow for creation of adaptive and responsive scenarios that can be dynamically modified in response to learners needs. For example, learners can participate in simulated stressful situations where they must immediately identify and correct communication breakdowns. Such learning contributes to the development of strategic competence, including the ability to clarify, confirm, and correct misunderstandings in stressful situations. This is consistent with more general educational concepts of “English for Specific

Purposes," which emphasize the importance of task-based learning and practical experience in the development of professional communication skills (Canale & Swain, 1980).

Despite of these advantages, the literature also highlights the challenges in putting AI and simulation technologies into practice. These include concerns about over-reliance on technology at the expense of human interaction, high cost of sophisticated simulation equipment and the need for instructor training. Pedagogical approaches that successfully integrate AI technologies into the curriculum are also needed to ensure that technology enhances rather than replaces communication skills. Ethical issues, including algorithmic bias and data privacy, are increasingly relevant in AI-based education (Zawaki-Richter et al., 2019).

In conclusion, artificial intelligence (AI) and simulation-based learning represent significant advances in maritime English education, offering creative solutions to long-standing challenges in English for Specific Purposes (ESP). These methods contribute to the development of both linguistic and operational communicative competences by providing personalized instruction, real-world practice and interactive learning opportunities. However, their successful application requires careful integration into pedagogical frameworks, ongoing teacher support and consideration of practical and ethical limitations.

3. Research Methodology

The study uses a mixed-method approach including quantitative and qualitative methods together with scenario-based assessment in order to measure the effectiveness of artificial intelligence-assisted maritime English teaching in improving students' competence in IMO Standard Maritime Communication Phrases (SMCP) and GMDSS emergency communications procedures.

4. Discussion of Results

4.1 Data of the 2nd year Students

Twenty responses were received from the second year BSMA Navigation faculty students who were given questionnaires with a link https://forms.gle/5PLudmENf8ZLEpaq9. To the first background information question 100% of respondents were identified as second-year students ensuring homogeneity of the same group.

Q No. 2, which evaluated students' understanding of the primary aim of SMCP, 5% chose "to standardize maritime communication" and 5% chose "to reduce misunderstandings in safety-critical situations"; 20% chose "ensuring clear communication between multilingual crews" as a goal and 75% of respondents have an incorrect or partial understanding of the basic goal of SMCP. Q No.3, which was about the key tasks of GMDSS, 40% of respondents properly chose automated distress alerting to shore stations and nearby ships," though 15% indicated "communication system for distress and safety". However, a significant proportion of students had misunderstandings: 35% associated GMDSS with routine ship-to-ship communications, 15% with weather forecasts, and only 10% with cargo handling procedures. These results indicate that a large majority of students lack clear conceptual knowledge of how the GMDSS operates. Q No. 4, which measured confidence in using the SMCP in emergency situations 75% of respondents chose Level 2 and only 5% chose Level 1 indicating low confidence. While Level 4 was chosen by 10% of respondents and none of the participants chose the highest level. This shows that 80% of students do not trust the use of SMCP during an emergency. For the fifth question, assessing the ability to structure a distress message in English, 40% of students chose level 2, while 35% chose level 1. However, 10% chose level 3, 15% chose level 4, and there were no answers at level 5. According to these data, 75% of students have difficulty adequately structuring distress messages. For the sixth question, which was about communication under pressure, 40% of the students chose level 1 and 40% chose level 2. Only 10% chose level 3, while 5% chose level 4 and 5% chose level 5. This means that 80% of respondents have difficulty communicating effectively under pressure. For the seventh question, which assessed students' awareness of the differences between MAYDAY, PAN-PAN, and SECURITE, 60% selected Level 3, 30% selected Level 4, and 10% selected Level 2. None of the students chose the highest level. These results indicate that although some students are aware of message priorities, most have only moderate knowledge in this regard.

As for the scenario-based questions following results were obtained: The Scenario 1, where the ship was on fire and urgent assistance was needed, only 5% of respondents chose the correct answer (MAYDAY), while 65% chose PAN-PAN and 30% chose SECURITE. This shows that 95% of the students did not correctly

identify the distress situation. In the scenario 2, where the engine breaks down without immediate danger, 20% of respondents correctly selected PAN-PAN. However, 70% chose MAYDAY and only 10% chose SECURITE. This indicates that most students overstate the severity of the case. To the scenario 3, 55% of respondents correctly selected SECURITE, 25% selected MAYDAY and 20% selected PAN-PAN, which was a floating hazard at sea. According to these results, 45% of students did not recognize the safety warning.

Students' perception of learning with the help of artificial intelligence was found to be very promising. 70% of respondents chose Level 4 and 25% chose Level 5 when asked whether AI- permitted activities could improve communication skills. Likewise, 55% of students chose level 4 and 40% - level 5 when it concerned the claim that AI can provide immediate feedback. Moreover, 65% of participants selected Level 4, 35% selected Level 5 when questioned if they would increase their trust in AI tools on a regular basis. These data show that among 95% of students, 45% did not recognize the safety warning. Student insights regarding the AI-assisted learning have been found to be very favorable. When asked “AI can provide immediate feedback on my mistakes”, 5% of students chose level 3, whereas the large scale of answers were a high level of agreement, 55% chose level 4, and 40% chose level 5. The levels 1 or 2 were not selected by any respondent. These results show that 95% of respondents consider AI a useful tool for immediate feedback. As for the “regular practice with AI tools will increase my confidence”, 65% chose level 4, 35% chose level 5, and none of the students chose levels 1–3, showing significant agreement. This shows 100% positive responses, indicating that everyone agrees that regular use of AI technologies can significantly progress confidence.

To the last question 75% of respondents stated having difficulty remembering the accurate phrases related to the use of maritime English in emergency situations. Additionally, 45% circled having difficulty communicating under pressure, 60% indicated lack of confidence when speaking and 40% confused MAYDAY, PAN-PAN and SECURITE. Additionally, 20% said they had little experience to real-life cases, 30% - had no hands-on training or simulations, and 35% of students indicated that they had difficulty establishing distress communications.

4.2 Data of the 2nd year Students

In this part of Survey, twenty responses were received from third year BSMA Navigation faculty students being provided the questionnaires with a link https://forms.gle/5PLudmENf8ZLEpaq9. The first background information question revealed that 100% of respondents represent homogeneity of the same group.

Q No. 2 "What is the main purpose of SMCP?" proved consistent awareness of its function in maritime communication. 95% of students chose "to reduce miscommunication in safety-critical situations", while 80% chose "to standardize maritime communication" and "to ensure clear communication between multilingual crews". Particularly, not any of the participants recognized features related to the SMCP, for instance, navigation charts or substituting English Language instruction. On the whole the results indicate on the importance of safety tools, standardized and effective communication at sea. Q No. 3 "What does GMDSS primarily provide?" demonstrated a detailed and consistent awareness of its essential responsibilities. The majority of respondents selected "distress alerting and emergency communication," which highlighted the importance of GMDSS being an important safety instrument at sea. None of the respondents selected distinct option, which demonstrated a good conceptual clarity. So, this part demonstrated that GMDSS is vital instrument for maritime safety and emergency response. Q No. 4 "I feel confident using SMCP in emergency situations" demonstrated high level of confidence among students. 60% of students strongly agreed being confident in using SMCP in distress cases. Only 15% expressed neutral views. Q No. 5 "I can clearly structure a distress message in English" demonstrated a high level of confidence within the scope of communication ability. 65% of students strongly agreed and only 15% of respondents remained neutral towards the issue. None of the students expressed their disagreement. On the whole, the respondents believed that they are well-prepared to plan and deliver distress signals, which showed a high level of competency in Maritime English communication. Results of Q No. 6 ‘I can communicate effectively under pressure" demonstrated that 55% of students have high confidence while communicating effectively under pressure. 15% chose neutral comments with none of the students expressing disagreement. On the whole, the results indicate that respondents are well-prepared to maintain effective communication under pressure. As for the issue "I understand the difference between MAYDAY, PAN-PAN, and SECURITE", it shows a high level of competence. 70% of students

strongly agreed that they clearly understand the difference between important maritime distress and safety signs. Only 5% of students selected a neutral option and none of the students disagreed. On the whole, this finding highlight that the 3rd year students have a strong and confident awareness of critical emergency communication

Regarding the scenario-based questions following results were obtained: Scenario 1: "A vessel is on fire and needs immediate assistance". 95% of students selected the appropriate response, admitting MAYDAY to be correct distress message in life-threatening situations. Only 5 % selected other option, demonstrating slight misunderstanding. In the Scenario 2: "A vessel experiences engine failure but is not in immediate danger" 90% of respondents selected PAN-PAN as the right urgency message. About the Scenario 3: "A floating hazard is detected at sea''. 90% of students selected proper response SECURITE and only 10% selected different answer, which demonstrates minimal ambiguity.

The following issue "AI-based exercises can improve my communication skills" expressed a very good opinion of AI-supported learning. 70% of respondents strongly agreed that AI-bases exercises can improve their communication skill, whereas 10% had neutral views. In general, the results indicate on positive impact using ai-based exercises while learning. Concerning the statement "AI can provide immediate feedback on my mistakes" demonstrated constructive attitude AI-supported learning. 75% of students highly agreed and only 5% selected a neutral variant. None of the students disagreed. This approach highlights that timely given feedback will positively benefit their learning and communication abilities. The statement "Regular practice with AI tools would increase my confidence" displayed a positive approach regarding AI-assisted learning. 80% of students strongly agreed and only 5 % selected a neutral option. This means that the 3rd year students appreciate AI tools for boosting communication skills. As for the last question "What difficulties do you face when using Maritime English in emergency situations?" 65% chose that communication under pressure to be the most frequently selected barrier, which highlights that the stress has a serious impact on communication skills. Additionally, 55% selected as a barrier insufficient vocabulary, though 50% assumed that barrier is caused by incorrectly arranged messages. Only 30% selected pronunciation as a barrier, which is not as crucial as previous ones but has its own importance while communication. To sum up, the findings demonstrate that although students have a theoretical understanding, actual communication under stress remains a major challenge in emergency situations.

5. Limitations of the Study

The data collected can be used as a basis for further research on this topic and provide valuable information about the students' knowledge of SMCP and GMDSS systems, as well as their views on AI-based learning. However, due to the relatively small number of maritime students from a specific institution, the sample is limited and not fully representative. Therefore, the results cannot be applied to a larger group of English language learners in maritime educational institutions. To improve the validity and generalizability of the results, it is recommended that future research be conducted via applying larger, more diverse sample of different maritime educational institutions and institutions, although the study provides a reliable representation of current trends within the sample group.

6. Conclusion

The results of the study show that second-year students still being the process of learning demonstrate low competence of the SMCP and GMDSS systems, as well as poor communication skills when answering questions related to the structure of the message. They also have low self-esteem and experience difficulties communicating under stress. The inability to accurately recognize the correct types of emergency messages in scenario-based tasks is a significant problem, revealing significant misconceptions. Students also showed a very positive attitude towards learning experience via applying AI tools, highlighting its great potential in terms of enhancing maritime communication skills.

Third-year students, on the other hand, demonstrate a strong and consistent understanding of the basic objectives and operating principles of SMCP and GMDSS. They are confident in their ability to use SMCP, organize distress messages and communicate clearly under stress. A solid practical understanding of MAYDAY, PAN-PAN, and SECURITE is demonstrated through their responses based on scenarios. Furthermore, students are very positive about AI-based training and acknowledge its benefits in boosting their confidence and

communication skills. However, despite a solid theoretical understanding, they still face some challenges, particularly in terms of message structure, limited language and communication under stress.

On the whole, the results of the study to large extent contribute to the above-stated purpose of the abstract and demonstrate that effective communication in Maritime English is essential for maritime safety and that current educational approaches need to be modified. Although SMCP and GMDSS competence is improving with advancement, students at the initial stage still face significant gaps in confidence, message structure and the correct use of emergency communication procedures, as shown by a comparison between second- and third-year students. These results highlight the importance of improving Maritime English instruction through more realistic, scenario-based methods. In line with the research objective, an overwhelmingly positive feedback from students on AI-based tools demonstrates how they can enhance their learning by offering a realistic communicative environment, interactive practice and immediate feedback. Thus, integrating AI-based learning into Maritime English curricula can successfully bridge the gap between theoretical understanding and real-world application, ultimately educating maritime professionals who are safer, more experienced and better prepared for the digital age.

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An Overview on Cybersecurity in the Maritime-Port Sector

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Abstract: Cybersecurity, defined as the set of processes, best practices, and technological solutions that help protect critical systems, data, and networks against digital attacks, has been a central topic in the international maritime community recently. Since 2017, a year particularly plagued by digital attacks on the maritime sector, *e.g.*, the NotPetya malware attack at Maersk irreversibly encrypting bootloader registers of main computers, the IMO has paid special attention to the issue of cybersecurity, particularly in regulatory terms. In fact, in 2016, the IMO's MSC approved document MSC.1/Circ.1526 that identifies vulnerable systems and sets the functional elements that support effective cyber risk management, leading to the MSC-FAL.1-Circ.3 in the following year. This circular has undergone regular updates, showing the organisation's commitment to updating systems in terms of digital security and raising awareness among all personnel. This paper summarises the most relevant documentation applied to cybersecurity on the maritime sector, focusing on digital piracy planning and attack execution, attack vectors for ships, and crisis response and prevention proposals for safer maritime transport.

Keywords: cybersecurity; cyber risk; vulnerable systems; digital piracy; digital security

1. Introduction

Smart and automated ports are becoming increasingly common worldwide to maintain the flow of goods, increase local safety, and mitigate occupational risks. However, this digital transformation requires a parallel advancement in cybersecurity. Significant attention has been given to the progressive need to protect computer systems on ships and in port administrations, safeguarding the entire supply chain through prophylactic and anticipatory security measures. The transition to Maritime 4.0 has introduced an unprecedented level of interdependency between Information Technology (IT) and Operational Technology (OT) (Potamos *et al.*, 2024). Typically, IT manages data-centric operations, terminal operating software, and logistics planning, prioritizing data confidentiality and integrity (Curvey, 2024). Data is crucial in the sector ensuring 90% of global trade, which is governed by OT that directly controls physical machinery (Progoulakis *et al.*, 2021). Because OT prioritizes availability and physical safety, both domains are interconnected, relying on IT inputs for efficient, automated cargo handling (Progoulakis *et al.*, 2021; Martínez *et al.*, 2024). Partnerships between technology leaders and maritime services aim to create resilient supply chains through smart logistics. While automation reduces human error in physical operations, it opens new surfaces for cyber threats. Professional experience indicates that the digital identity of a maritime organisation is now as vital as its physical infrastructure. Aligning deeply with the human-centred theme, the safety of digital oceans depends fundamentally on the awareness and continuous training of all personnel, from senior management to seafarers. This paper is structured as follows: Section 2 introduces the context of cybersecurity in the maritime sector and its supporting industry; Section 3 resumes the most relevant International Maritime Organisation (IMO) and International Association of Classification Societies (IACS) regulations; Section 4 presents vulnerabilities and attack vectors; Section 5 draws mitigation proposals; Section 6 summarises; and Section 7 draws conclusions.

2. Industrial Players Role in Maritime Cybersecurity

As digitalization accelerates within the maritime sector, embedding robust cybersecurity measures has become a critical imperative. While fostering security awareness is an essential first step, it is insufficient to mitigate evolving threats (de la Peña Zarzuelo, 2021). Thus, cybersecurity must be integrated proactively during the initial design phase of modern systems rather than treated as a retrospective add-on (IAPH, 2025). Modern

infrastructure should be inherently compliant with sector-specific cybersecurity standards. However, because these tailored frameworks remain incomplete, established industrial standards, *e.g.*, IEC/ISO, NIST/NSA, and IEEE, must serve as baseline. Within this paradigm, strategic pathways to integrate leading cybersecurity firms into the maritime ecosystem is essential to drive technical advancement and industry maturity. CISCO is a world leader in computer networking and information security and a key partner of Inchcape Shipping Services (ISS). ISS is a company specialised in digital solutions for the maritime sector, founded in 1847 through a mercantile partnership (Cisco, 2008), and a key British multinational port and maritime management company headquartered in London. Similarly, Huawei collaborates with port operators to develop smart logistics that enhance supply chain resilience (Huawei, 2024). Smart and automated ports, which maintain the flow of goods, improve local safety, and mitigate occupational risks, are becoming increasingly prevalent worldwide.

3. IMO and IACS Regulatory Framework

The IMO has led the regulatory response to digital threats, intensifying its focus since the 2017 surge in maritime cyberattacks. Since 2017, a year particularly plagued by digital attacks on the maritime sector, the International Maritime Organisation has paid special attention to the subject of cybersecurity, notably in regulatory terms. In fact, in 2016, the IMO's Maritime Safety Committee (MSC) approved document MSC.1/Circ.1526, which led to the creation of document MSC-FAL.1-Circ.3 the following year (IMO, 2016; IMO, 2025). This second circular, in turn, has undergone regular updates, demonstrating the organisation's commitment to updating systems in terms of digital security and raising awareness among all personnel involved within the sector. Similarly, Resolution MSC.428(98) was established in 2017 accordingly, and, more recently, in 2021 the MSC 104/7/1 guidelines were developed (IMO, 2017; IAPH, 2021). All the documentation will be detailed in this section, with emphasis placed on their respective fundamental aspects. During its 96th session in May 2016, the MSC approved the interim guidelines on maritime cyber risk management (MSC.1/Circ.1526), addressing the urgent need to raise awareness of cyber threats. This document laid the foundation for MSC-FAL.1-Circ.3, which is the primary reference for IMO Model Courses 3.24, of 2018, and 3.26 of 2023, and is expected to be integrated in all security-related Model Courses, from 3.19 to 3.27. A pivotal milestone was adopting Resolution MSC.428(98) in 2017, which formally incorporates cyber risk management into the Safety Management Systems of the International Safety Management (ISM) Code. Furthermore, the MSC 104/7/1, of 2021, and MSC 110/7/1, of 2025, guidelines prioritised port facility security, supported by the International Association of Ports and Harbours (IAPH) following a surge in cyber threats since the COVID-19 pandemic. Complementing IMO, the IACS Recommendation No. 166, of 2020, sets a technical framework for cyber resilience, asserting that prevention is more important than cure (IACS, 2020). To summarise:

- MSC.1/Circ.1526 - 2016 - Interim Guidelines on Maritime Cyber Risk Management,
- MSC-FAL.1-Circ.3 - 2017 - 2025 (Rev3) - Guidelines on Maritime Cyber Risk Management,
- MSC.428(98) - 2017 - Maritime Cyber Risk Management in Safety Management Systems,
- MSC 104/7/1 - 2021 - Measures to Enhance Maritime Security - IAPH Cybersecurity Guidelines for Ports and Port Facilities,
- MSC 110/7/1 - 2025 - Revision of the Guidelines on Maritime Cyber Risk Management and Identification of Next Steps to Enhance Maritime Cybersecurity - IAPH Cyber Resilience Guidelines for Emerging Technologies.

3.1. MSC.1/Circ.1526 - 2016

This document focuses on high-level recommendations for maritime cyber risk management, outlining the measures necessary to protect maritime transport against current and emerging threats related to digitalisation. Risk management is key to safe and secure shipping operations. The primary objective is to support resilient shipping by identifying the following systems as particularly vulnerable: 1) Bridge systems; 2) Cargo handling and management systems; 3) Propulsion, machinery management, and power control systems; 4) Access control systems; 5) Passenger service and management systems; 6) Public passenger networks; 7) Administrative and crew welfare systems; 8) Communication systems. Furthermore, the circular distinguishes between IT, defined as the use of data as information, and OT, defined as the use of data to control or monitor physical processes. Threats may arise from malicious actions, such as hacking or malware injection, or from unintentional

consequences of benign actions, including software maintenance or user permission errors. These actions expose vulnerabilities, e.g., outdated software or ineffective firewalls, exploiting weaknesses in both IT and OT.

3.2. MSC-FAL.1/Circ.3/Rev.3 - 2025

The relevance of this circular is in establishing the urgent need to raise awareness of cyber threats and vulnerabilities. By providing high-level recommendations, it presents risk management as a fundamental aspect of safe maritime operations, aiming for cyber-resilient shipping. The document establishes key definitions: 1) Computer Based System (CBS) is a programmable electronic device or interoperable set of devices organised for specific purposes; 2) Cyber Incident is an occurrence that results in adverse consequences for a CBS; 3) Cyber Risk Management is the process of identifying, analysing, assessing, and communicating cyber risks; 4) IT encompasses all CBSs focused on using data as information; 5) OT includes all CBSs focused on using data to control or monitor physical processes. Cyber risks arise from malicious actions or unintentional, careless acts, such as poor software maintenance, that exploit vulnerabilities in CBS design, integration, or maintenance. Exploiting these weaknesses—directly via weak passwords or indirectly through lack of network segregation—impacts data confidentiality, integrity, and availability. Effective management must also consider external suppliers and start with top management, fostering a culture of cyber-awareness. Furthermore, circular MSC-FAL.1/Circ.3 introduces the 'Govern' element (Table 1), aligned with the National Institute of Standards and Technology (NIST) Cybersecurity Framework 2.0, to establish strategies, define roles, and ensure business continuity through crisis management and backups (NIST, 2024).

3.3. Resolution MSC.428(98) - 2017

In 2017, the IMO Maritime Safety Committee established the most relevant document for both the present and future, keeping in mind MSC-FAL.1/Circ.3; recalling resolution A.741(18), by which the Assembly adopted the International Management Code for the Safe Operation of Ships and for Pollution Prevention, the International Safety Management Code - ISM Code; and noting the objectives of the ISM Code, which include providing safe practices in ship operations and a safe working environment, assessing all identified risks to ships, personnel, and the environment, establishing appropriate safeguards, and improving the safety management skills of personnel ashore and aboard ships (IMO, 2017). Accordingly, it affirmed that an approved safety management system must take cyber risk management into account in accordance with the objectives and functional requirements of the ISM Code; encouraged Administrations to ensure that cyber risks are appropriately addressed in safety management systems; recognised the necessary precautions that may be required to preserve the confidentiality of certain aspects of cyber risk management; and finally, requested Member Governments to bring this resolution to the attention of all relevant stakeholders (IMO, 2017).

3.4. MSC 104/7/1 - 2021 and MSC 110/7/1 - 2025

The IAPH cybersecurity guidelines for Ports and Port Facilities were submitted by the IAPH to the IMO Maritime Safety Committee in 2021. This proposal, which placed cybersecurity at the top of the priority list, indicates that ports and port facility stakeholders are reporting significant increases in cyber threat activities, especially since the onset of the COVID-19 pandemic. It is reported that cyberattacks against OT systems increased by 900% between 2017 and 2021, and the risk of a cyberattack has become the primary risk for port authorities. It is proposed that port executives must recognise the importance of managing cyber risk. It is clearly stated by the IAPH that it is essential for executives to develop a strategy and a cyber risk management plan to achieve and sustain a defence-in-depth posture, providing key knowledge and information on 21st century cyber threats. Establishing organisational cyber awareness to address the human element as a principal component is crucial. Finally, as cybersecurity represents a collective responsibility not limited solely to the IT department, the guidelines demonstrate how cybersecurity capacity can drive cyber resilience: port executives take the lead in allocating resources to deal with security, actively managing governance, creating an organisational culture to support cybersecurity (IAPH, 2021). In 2025, IAPH Cyber Resilience Guidelines for Emerging Technologies in the Maritime Supply Chain endorses the integration of cybersecurity in the early stages of development - cybersecurity by design - which is essential, but depends on compliance standards that must be improved, and the use of artificial intelligence to monitor abnormal activity, network traffic and user behaviour (IAPH, 2025).

3.5. Mandatory Integration and Technical Standards

Resolution MSC.428(98), of 2017, is the most significant milestone, as it mandates that cyber risks be addressed within the Safety Management Systems (SMS) under the ISM Code. Furthermore, the IACS Recommendation No. 166, of 2020, provides technical requirements for cyber resilience, emphasising that "prevention is more important than cure" through rigorous verification tests (IMO, 2017; IACS, 2020).

4. Vulnerabilities and Mitigation

As a specialised agency of the United Nations responsible for measures to improve the safety and security of international shipping and to prevent marine pollution from ships, the IMO is also involved in legal matters, including liability and compensation issues and the facilitation of international maritime traffic. According to the IMO, maritime cyber risk refers to a measure of the extent to which a technology asset could be threatened by a potential circumstance or event, which may result in operational, safety, or security failures related to shipping because of information or systems being corrupted, lost, or compromised. Therefore, it is essential to list the most common types of threats in the cyber environment: malware, phishing, denial of service, spyware, exploitation of vulnerabilities, password attacks, attacks on Internet-of-Things (IoT) devices, social media attacks, and man-in-the-middle attacks.

Table 1. Functional elements for effective maritime cyber risk management.

Element	Primary Objective	Key Activities and Responsibilities
Govern	Strategy & Oversight	Risk management policies; define roles; ensure business continuity.
Identify	Asset Awareness	Maintain hardware/software inventories; document data flows.
Protect	Safeguards	Implement access controls (MFA); train personnel; manage backups.
Detect	Monitoring	Continuous network monitoring to find adverse events in real-time.
Respond	Incident Action	Execute response plans; notify stakeholders; contain threats.
Recover	Restoration	Restore affected systems; verify backup integrity; reviews.

4.1. Key Definitions

The key definitions can be listed as follows:

- Malware: Malicious software capable of infecting IT and OT systems, compromising the safety and operation of vessels and ports,
- Ransomware: A specific type of malware that encrypts data and demands a ransom for its release. A landmark example is the NotPetya attack that affected Maersk in 2017, causing significant disruptions to the global supply chain,
- Phishing: Attempts to obtain sensitive information through fraudulent emails,
- Distributed Denial of Service (DDoS): Attacks that overwhelm systems with excessive traffic, rendering them unavailable. These attacks can paralyse port and navigation operations,
- Password Attacks: Includes brute-force attacks, involving repeated attempts to guess a password, or dictionary attacks, using common words or known passwords to identify the correct one,
- IoT Device Attacks: Exploitation of vulnerabilities in IoT devices to access networks and data,
- Spyware: Software that monitors a user's activities without their knowledge or consent, often for the purpose of information theft,
- Man-in-the-Middle (MitM): Interception of communications between two parties, allowing the attacker to read, modify, or inject data during the exchange,
- Exploitation of Vulnerabilities: Taking advantage of security flaws in software or systems to gain unauthorised access,
- Social Engineering: Manipulation of users to obtain confidential information through psychological deceit,
- Fake Accounts or Fraud: Use of false profiles or involvement in fraud on social media platforms.

4.2. Applied Context in the Maritime Industry

In the maritime industry, as in others, attackers include competing nations, criminal organisations, small groups, individuals, employees, insiders, service providers, cyber pirates, hacktivists targeting the maritime industry, professional criminals, and cyberattacks directed at passengers, luggage, cargo, catering, systems, staff, and all individuals with authorised access to systems and data. In the maritime sector, as elsewhere, attackers employ the same cybersecurity techniques to attempt to obtain information that leads to unauthorised access. Understanding how pirates plan and execute an attack is a highly relevant aspect:

- Step 1 - Information gathering regarding personnel and systems,
- Step 2 - Identification of potential targets and victims,
- Step 3 - Assessment, recruitment, and testing,
- Step 4 - Privilege escalation,
- Step 5 - Identification of key clients,
- Step 6 - Attack on critical infrastructure, as defined in (IACS, 2020).

It is essential to consider the workforce, including their weaknesses and vulnerabilities, to mitigate potential collusion with external parties or susceptibility to cases of blackmail. Prophylactic measures at both management and shipowner levels are essential in this context (IMO, 2025). The Baltic and International Maritime Council (BIMCO) guidelines are widely used within the industry to implement effective cybersecurity measures. Cybersecurity frameworks are recommended; systems such as NIST, Center for Internet Security (CIS), and Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) ISO/IEC 27001 are regularly used to assess and improve security within the maritime industry (BIMCO, 2021).

4.3. Cybersecurity Attack Vectors for Ships (Entry Points)

The following points represent potential vectors for an attack or entry into a vessel's systems: satellite communication antennas, *e.g.*, satellite communications; Electronic Chart Display and Information System (ECDIS) navigation systems; Automatic Identification System (AIS) systems; onboard IoT sensors; crew Wi-Fi networks; unsecured Universal Serial Bus (USB) ports; remote engine control stations; cargo equipment and cranes (automated loading systems); remote access via Virtual Private Network (VPN); and social engineering. The incident involving Maersk and the NotPetya malware is one of the most notorious in the history of cyberattacks. Specific details of the attack include after infiltrating the computer networks of a Maersk vessel, the malicious software irreversibly encrypted the computers' boot records, the deepest part of a machine, which identifies the location of the operating system. It is crucial to note that NotPetya permanently encrypts the computers it infects; due to the nature of the encryption process, reversal is impossible even after a ransom is paid. The increasing digitalisation and automation of maritime systems, from ships to smart ports, has brought operational benefits but has also exposed new vulnerabilities. Some of the most critical risks include:

- High Interconnectivity: The link between navigation systems, engines, IoT sensors, and logistics management platforms creates a vast attack surface. A single vulnerable point can compromise the entire network,
- Industrial Control Systems/Supervisory Control and Data Acquisition (ICS/SCADA): These systems often run on outdated software, becoming targets for malware, *e.g.*, Stuxnet or WannaCry,
- Lack of Network Segmentation: The absence of separation between OT and IT networks allows an attack via email or crew Wi-Fi to propagate to critical shipboard systems,
- Inside Threats: Employees with privileged access may, intentionally, through negligence, or even under blackmail, compromise system security,
- Social Engineering and Phishing: Crews and port operators are frequently targets of sophisticated phishing campaigns that exploit trust and operational routines,
- Lack of Updates and Patching: Many maritime systems operate with software that is not regularly updated, leaving known vulnerabilities open to exploitation,
- Integration with Port Systems: The connection between vessels and port infrastructures (such as automated cranes and registry systems) can be exploited to launch supply chain attacks.

5. Towards Safer Maritime Transport

The primary objective immediately following an attack is to ensure that the organisation can recover swiftly with the minimum possible impact. The team responsible for implementing the incident response plan must be properly trained and permanently prepared to act quickly and effectively. A post-incident analysis is essential to identify security system failures and implement improvements to prevent similar occurrences in the future. Furthermore, transparency and clear communication among all stakeholders throughout every phase of the plan are fundamental to maintaining the organisation's trust and reputation during a security incident. An incident response plan is a set of procedures that guide an organisation on how to react when facing an attack or security breach. It defines the actions to be taken immediately upon identifying an incident, aiming to minimise damage, restore operations, and ensure that the same type of attack fails in the future. The incident response plan also encompasses crisis communication and the coordination of efforts between the everybody involved in resolving the problem, providing benefits that will be perceived across the entire affected chain.

5.1. Essential Vectors for Crisis Response and Prevention

It is important to remember that the affected parties are not limited exclusively to the organisation hit by the incident; they also include partners, suppliers, other stakeholders involved in the process, and, most importantly, the customers. Cybersecurity is essential to ensure data protection and digital efficiency, particularly in contexts involving sustainability and environmental management. While the digitalisation of organisations and the increasing reliance on information and communication technologies bring significant benefits, they also heighten the risk of cyber threats. Furthermore, digital efficiency involves the use of digital technologies to improve operational efficiency and reduce environmental impact. This may include the implementation of energy management systems, real-time environmental monitoring, and process optimisation through data analytics. Consequently, two essential vectors for crisis reaction and prevention emerge:

- Crisis Management and Data Protection: Crisis management and data protection are essential to ensure information security during emergencies. This includes the implementation of security protocols and the use of cybersecurity technologies to protect sensitive data,
- Monitoring and Efficiency: The use of environmental monitoring technologies can help improve the efficiency of natural resource management. This point encompasses the use of sensors and data analytics systems to monitor air, water, and soil quality, facilitating informed decisions for environmental preservation. These points highlight the significance of cybersecurity in protecting environmental data and promoting digital efficiency.

In an interconnected world, digital identity has become as critical as physical infrastructure in the maritime sector. Ports, vessels, and logistics systems utilise digital networks to coordinate operations, manage cargo, and communicate in real-time with international entities. However, this increasing digitalisation brings with it a growing risk: cyber threats that can undermine both the reputation and the overall functioning of a company.

5.2. Best Practices for Protecting Identity and Enhancing Digital Security

Digital identity represents an organisation's entire online presence, encompassing communication systems, websites, databases, and private operational networks. A successful attack can compromise, among other aspects: navigation and logistics data, confidential information from customers and partners, internal and external communication, and the integrity of equipment and IoT sensors. The impact extends beyond immediate financial losses; the trust of the market, customers, and regulatory bodies can be severely undermined. In particular, the following measures are encouraged:

- Invest in monitoring and intrusion detection systems,
- Conduct regular cybersecurity audits,
- Provide continuous training for employees on digital risks,
- Develop a comprehensive incident response plan,
- Maintain transparent communication channels in the event of an incident.

Prophylactic protection best practices include:

- Training and Awareness: It is essential to educate employees on security best practices, including how to identify and respond to cyber threats,
- Regular Updates: Keeping systems and software up to date protects against known vulnerabilities,

- Continuous Monitoring: Implementing continuous monitoring solutions to quickly detect and respond to security incidents,
- Access Policies: Defining clear access policies and ensuring that only authorised users have access to sensitive information,
- Data Backup: Regular data backups to ensure recovery in the event of an attack or system failure,
- Cybersecurity by design in modern systems development, and not as an add-on layer, is crucial.

Digital security tools include:

- Firewalls: Essential technologies for protecting networks against unauthorised access. They monitor and control inbound and outbound traffic based on predefined security rules,
- VPNs (Virtual Private Networks): VPNs are crucial for ensuring secure and encrypted connections between remote devices and the corporate network, helping to protect data transmitted over public networks,
- Intrusion Detection and Prevention Systems (IDS/IPS): These tools monitor the network for suspicious activities and can block attacks in real-time,
- Multi-Factor Authentication: MFA adds an extra layer of security, requiring multiple forms of verification before granting access to systems and data,
- Encryption: Encryption is fundamental for protecting data both in transit and at rest, ensuring that only authorised users can access it.

The maritime sector presents unique challenges for digital security, particularly in remote operations. Best security practices in this context include:

- Secure Connections: VPNs and encryption to ensure that communication between vessels and the base are secure,
- Device Monitoring: Implementing monitoring systems to track and protect remote devices, *e.g.*, sensors and navigation equipment,
- Incident Response: Developing and testing incident response plans specifically designed for maritime operations,
- Protection against Physical Threats: Ensuring that physical devices are protected against unauthorised access and damage,
- Critical Technology: Automatic Identification System (AIS) and Global Positioning System (GPS) manipulation can be mitigated by cross-referencing data with independent radar or Inertial Navigation Systems (INS) systems to detect discrepancies in reported positions (Ben Farah et al., 2022), machine learning models can scan AIS data feeds for abnormal behaviours (IAPH, 2025) and be applied on both the real vessels and in their corresponding digital twin counterparts,
- Digital Twins and Remote Operation Centers (ROCs): Prevent corrupt data input from the real vessel with a zero-trust approach covering the entire data pipeline with edge cryptography, cross-referencing and redundant communication channelling,
- Training: Simulate attack scenarios and mitigation procedures (redundancy-to-regain).

These tools, along with the performance of regular practical training exercises and evaluations, are essential for enhancing digital security, particularly within the context of remote access and operations.

6. Summary of Vulnerabilities, Attack Vectors and Mitigation Proposals

The increasing digitalisation of maritime systems has exposed critical vulnerabilities in bridge systems (ECDIS/AIS), cargo management, propulsion control, and crew welfare networks.

6.1. Attack Entry Points and Digital Piracy Execution

Vessels are vulnerable through vectors, *e.g.*, satellite communication antennas, unsecured USB ports, crew Wi-Fi, and remote access. Social Engineering remains a primary threat, where attackers exploit human routine and trust through phishing campaigns. Digital pirates follow a structured six-step execution methodology: (1) Information gathering, (2) Target identification, (3) Assessment and testing, (4) Privilege escalation, (5) Client/Data identification, and (6) Attack on critical infrastructure. The NotPetya incident remains a landmark case where malware irreversibly encrypted computer bootloader registers, causing total operational paralysis.

6.2. Best Practices for Digital Security

To ensure safer maritime transport, the following prophylactic measures are proposed:

- Segmentation: Logical separation between critical OT and administrative IT/Crew networks,
- Multi-Factor Authentication: Mandatory verification layers for all system access,
- Encryption: Protecting data in transit and at rest using robust digital tools,
- Continuous Awareness: Regular training for all staff on identifying digital risks.

7. Conclusion

In this paper, the most relevant IMO documentation applied to cybersecurity was explored, alongside its historical framework and a summary of some of the most significant reported case studies. The most vulnerable systems were identified, as well as their weaknesses and the elements of active support in cyber security risk management within this sector. Through its regulations, the IMO has made it clear that cybersecurity involves all personnel in the maritime sector (from senior to junior levels), requiring the establishment of strategies for risk management, identification, protection, detection, response, and recovery. The IMO's International Convention for the Safety of Life at Sea (SOLAS) has included requirements for cybersecurity onboard ships since 2021 (IMO, 2024). Attention must be total and constant, as negligence is the primary gateway to security breaches. Prevention and specific training are essential. The IMO's regulations, particularly the integration into the ISM Code and SOLAS requirements since 2021, make it clear that digital security is now a fundamental requirement for the safety of life at sea. Prevention and specific training are essential to protect the global supply chain and maritime economy against evolving digital threats. Finally, specific standards for cybersecurity in the maritime sector must be clarified ant set, so modern systems can be designed to comply from start (IAPH, 2025).

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Human reliability assessment in digitized maritime operations using data-driven Bayesian networks

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Abstract: Maritime transport is undergoing rapid digital transformation, yet accident outcomes remain strongly influenced by human performance under operational constraints. This study develops a human-centered Bayesian Network (BN) model to quantify how interacting human, system, and contextual factors influence accident severity. A dataset of 427 accident investigation reports (2000–2020) was coded into structured variables covering cognition, human–system interaction (HSI), bridge team performance, and operational context. The BN model was learned through A Tree-Augmented Naïve Bayes (TAN) model, parameters estimated using Expectation–Maximization (EM), and evaluated via stratified 10-fold cross-validation, achieving strong discrimination (AUC = 0.835–0.967). Results show that severity escalation is driven by degraded situational awareness, poor decision-making, challenging context, and ineffective communication, with digital interaction failures acting as key amplifiers. Scenario analysis demonstrates that combined operational stressors yield up to 73% probability of very serious outcomes, while resilient conditions eliminate catastrophic risk. The model provides actionable insights for competency-based training and supports safer human–automation integration in digital maritime operations.

Keywords: Human-centered digital oceans; maritime safety; Bayesian Network; bridge team training; human–machine interaction

1. Introduction

Maritime operations are being rapidly digitized through e-navigation services, increasingly integrated bridge ecosystems, and broader automation/autonomy initiatives, with the stated aim of improving safety, efficiency, and environmental performance (Martínez de Osés and Uyà Juncadella, 2021, Palma, 2024, Giglio et al., 2025). Yet recent industry evidence frames digitization as a socio-technical transition that could overwhelm beyond empowering crews when data flows, alarms, and heterogeneous interfaces accumulate with insufficient coherent integration (inmarsat, 2025, Weintrit, 2011, Dewi, 2025). For example, the Future of Maritime Safety Report 2025 explicitly warns against contradictory outputs and stresses that "the aim should be to empower crews, not overwhelm them," positioning digitalization challenges and human factors as continuing determinants of safety outcomes (inmarsat, 2025). Complementing this, recent empirical work on officer seafarers reports measurable technostress associated with digitalization, reinforcing that digital transformation can introduce new performance-shaping pressures rather than simply removing workload (Bayrak and Muslu, 2025).

A growing body of work points to digital-era failure modes that are strongly human-centered: alarm fatigue, information overload, non-intuitive interface design, and difficulty understanding automation logic and uncertainty. Lloyd's Register highlights that increasing sensorization and alarm functions can lead to alarm fatigue that degrades operational awareness and performance, and notes the absence of strong regulatory instruments that require justification of the "safety credit" claimed by alarms (Hosny and Mohmed, 2026, Schliemann-Haug et al., 2025, Register, 2024). Field-facing evidence aligns: a recent alarm-management study synthesizing narratives from 65 watchkeeping officers (15 ships; 10 companies) reports both the operational value of alarms and persistent structural problems in alarm management that require urgent attention (Schliemann-Haug et al., 2025). Regulatory/assurance activity has also intensified around bridge alert management (e.g., IEC 62923-1/-2 becoming applicable for equipment installed after August 2021 in the

EU/EEA), reflecting recognition that alert handling and presentation are safety-critical aspects of modern bridge operations (DNV, 2021). Alongside alarms, interface diversity across manufacturers and systems is a recognized contributor to operator confusion and costly familiarization burdens, motivating standardization initiatives such as S-Mode concepts and grouping guidelines (Weintrit, 2019).

Equally important is the human-automation relationship: empirical research with maritime pilots shows limited formal training on predictor automation, reliance on self-learning, and difficulties detecting sensor error and understanding system function, conditions that can produce both misuse and disuse of automation and hence unsafe adaptation under time pressure (Westin and Lundberg, 2025). Qualitative evidence from automated shipboard contexts similarly reports that trust can evolve into overreliance, and that professional identity and perceived "good seamanship" shape how officers calibrate reliance on automation (Aalberg et al., 2024). Broader mixed-method work on safe automation and autonomy implementation emphasizes persistent needs for human control, override capability, and measures to counter complacency, reinforcing that safe digitalization depends on human-centered system design and training rather than automation alone (Aalberg and Kongsvik, 2026).

Across contemporary maritime safety research, accident causation and escalation are repeatedly linked to non-technical skills and human reliability constructs such as situational awareness (SA), decision-making quality, and bridge team coordination, especially under adverse or time-critical conditions (Kuzu, 2026, Chan et al., 2022, Hansen and Nazir, 2024). Simulator-based and BN-oriented human reliability work continues to operationalize SA as a central reliability mechanism, consistent with the view that degraded SA is a recurrent contributor to unsafe outcomes in complex operational settings (Nizar et al., 2024). Communication is a particularly well-evidenced bridge-team vulnerability in modern operations, including multicultural/linguistic factors and the fragility of closed-loop communication practices. Recent quantitative risk studies explicitly argue that the literature quantifying language/communication-induced risk has been limited and then provide Bayesian/fuzzy Bayesian quantification of how language proficiency, role/regulation violations, and related factors elevate accident risk (Yin et al., 2024). Complementary work using VDR-informed constructs and linguistic factors shows that lexical ambiguity and standardized phraseology misalignment can drive large changes in estimated accident risk, again highlighting that "human-centered" does not mean "qualitative only" (Yin et al., 2025). Moreover, systematic review evidence suggests that even when human reliability factors (e.g., fatigue) are well recognized, they can be underreported in official investigations, creating bias and uncertainty for reliability modeling unless explicitly addressed in data preparation and inference methods (Crestelo Moreno et al., 2022, Crestelo Moreno et al., 2026).

From a methodological perspective, BNs, valued for probabilistic reasoning and interpretability, have been widely adopted to model interacting risk-influencing factors using global and regional accident databases (Li et al., 2023, Liu et al., 2026). Notably, TAN-form BN and EM parameter learning are increasingly used in maritime accident studies to handle interdependencies and missing data while maintaining tractable structure learning (Fan et al., 2020). Yet much of this literature is primarily oriented toward risk factor ranking or broad accident attributes (type/severity/loss) rather than building a training-relevant human reliability model (Westin and Lundberg, 2025). Taken together, recent evidence indicates a clear gap: accident investigations and human factors studies increasingly discuss digital-interaction contributors (alarm load, interface complexity, automation misunderstanding, trust miscalibration), however these contributors are still rarely transformed into an interpretable probabilistic model that can quantify how combinations of human, system, and context conditions shift accident consequence severity, precisely the information needed to design training that is both safety-critical and operationally credible (Westin and Lundberg, 2025, Guo et al., 2025, Fan et al., 2020, Fan and Yang, 2023).

This study addresses that gap by contributing: i) Evidence-to-model translation: systematic coding of investigation-report narratives into a structured dataset spanning cognition/decision processes, human–system interaction, bridge-team factors, and operational/environmental context, aligned with emerging efforts to structure report text for causal analysis while improving consistency of human-factor representation. ii) Interpretable severity-focused probabilistic modeling: a TAN Bayes BN learned from accident-report-derived data with EM parameter estimation, leveraging a modeling lineage increasingly used in maritime accident analytics while targeting explicit human reliability and digital-interaction constructs. iii) Training- and decision-support relevance: model evaluation framed for consequence discrimination and scenario reasoning

(rather than description alone), supporting competency-based prioritization in training domains already recognized as critical for automation-era operations (e.g., calibrated trust, alarm/attention management, and bridge-team communication under uncertainty).

2. Methodology

BNs are particularly suited to maritime human reliability analysis due to their ability to model uncertainty, integrate heterogeneous data sources, and capture conditional dependencies among human, technical, and contextual factors (Khan et al., 2026). In safety-critical domains such as digitized maritime operations, where data are sparse, incomplete, and often derived from qualitative reports, BNs provide a transparent probabilistic framework that supports both predictive and diagnostic inference. This makes them well aligned with the objective of translating accident investigation evidence into interpretable, decision-support models for training and risk mitigation (Yin et al., 2025, Liu et al., 2025).

2.1 Data Description and Variable Construction

The dataset comprises 427 maritime accident investigation reports spanning 2000–2020, sourced from major international databases (IMO, 2000-2020, EMCIP, 2000-2020, MAIB, 2000-2020, NTSB, 2000-2020, TSB, 2000-2020, ATSB, 2000-2020). Each report was systematically coded into a structured dataset capturing four domains: (i) human cognition and decision-making (e.g., situational awareness, decision quality), (ii) human–system interaction (e.g., alarm effectiveness, display integration, mode awareness), (iii) bridge team factors (e.g., communication quality, coordination), and (iv) operational and environmental context (e.g., time pressure, weather, traffic complexity).

2.2 Network and Parameter Learning

The BN structure was learned using the TAN algorithm implemented in GeNIe Modeler. Conditional probability tables (CPTs) were estimated using the EM algorithm in GeNIe. EM iteratively maximizes the likelihood of the observed data by alternating between two steps:

Expectation (E-step): Compute the expected sufficient statistics given current parameter estimates(Liu et al., 2025): $Q(\theta \mid \theta(t)) = E[\log P(X, Z \mid \theta)]$ (1)

where X denotes observed data and Z represents latent or missing variables.

Maximization (M-step): Update parameters by maximizing the expected log-likelihood: $\theta(t+1) = \arg\max Q(\theta \mid \theta(t))$ (2)

This iterative process continues until convergence, yielding robust CPT estimates even in the presence of missing entries and sparse observations. The model was validated through 10-fold cross-validation with reported AUC values for model performance evaluation.

3. Results and Discussion

This study provides a quantitatively grounded, human-centred framework for understanding accident severity in digitized maritime operations by systematically translating qualitative accident investigation evidence into a probabilistic structure. Unlike conventional descriptive analyses, the developed BN enables simultaneous evaluation of interacting human, system, and contextual factors, allowing for both predictive and diagnostic insights. This is particularly significant for training and operational design, as it identifies not only individual risk contributors but also critical combinations of conditions (e.g., communication breakdown under high time pressure and complex environments) that disproportionately escalate accident severity. The model thus supports targeted, competency-based interventions aligned with real operational constraints. The details of the variables considered in this study, along with their classified states, are provided in Table 1.

Table 1. Considered variables as nodes and their classified states

Node	States	Node	States
Accident_Outcome_Severity	Near miss; Minor; Serious; Very serious	Situational_Awareness	Adequate; Degraded; Lost
Decision_Making_Quality	Appropriate; Delayed; Incorrect	Bridge_Team_Performance	Effective; Ineffective
Human_System_Interaction	Effective; Ineffective	Communication_Quality	Clear; Poor
Role_Responsibility_Clarity	Clear; Unclear	Mode_Awareness	Clear; Confused
Trust_in_Automation	Appropriate; Miscalibrated	Alarm_Management_Effectiveness	Effective; Ineffective
Sensor_Display_Integration	Integrated; Fragmented	Information_Overload	Low; Medium; High
Interface_Complexity	Low; High	Training_for_Digital_Systems	Adequate; Inadequate
Team_Based_Digital_Training	Adequate; Inadequate	Time_Pressure	Low; High
Fatigue_Level	Low; High	Traffic_Density	Low; High
Weather_Visibility	Good; Poor	Environmental_Complexity	Low; High
Operational_Context	Normal; Challenging	Automation_Bias	Low; High

3.1 Model Validation and Prediction Analysis

The TAN-BN demonstrated strong discriminative performance across all four accident outcome states, with AUC values ranging from 0.835 to 0.967, as shown in Table 2. The highest discrimination was obtained for near-miss and very serious accident, indicating that the model separates both low-consequence and catastrophic cases particularly well. Performance for Minor accident was also strong, while Serious accident showed comparatively lower but still robust discrimination. Overall, these results confirm that the model has sufficient predictive reliability for severity-state classification and is suitable for subsequent inference, scenario analysis, and training-oriented decision support.

Table 2. AUC values for the target node states during model validation

Severity state	AUC
Near miss	0.967467
Minor accident	0.906988
Serious accident	0.835269
Very serious accident	0.934592

After model validation, the next step is model prediction analysis, as shown in Figure 1. The marginal distribution of *Accident_Outcome_Severity* indicates a dominance of Very serious (42%) and Serious (26%) outcomes, with comparatively lower probabilities for Minor (24%) and Near miss (8%), suggesting that once adverse conditions emerge, the system tends to escalate toward higher consequence states rather than remain benign. Across the network, this escalation is consistently associated with degraded human-centered variables, notably Situational Awareness (Degraded/Lost = 73%), Decision-Making Quality (Delayed/Incorrect = 63%), and Human–System Interaction (Ineffective = 48%), alongside operational stressors such as Challenging context (68%), High environmental complexity (58%), and Poor communication (63%). These patterns reflect a coupled failure mechanism in which cognitive degradation and digital interaction deficiencies co-evolve under operational stress, rather than acting independently. For instance, high information load (≈68% medium–high) and fragmented sensor integration (~49%) likely contribute to attentional saturation and reduced situational awareness, which in turn propagates into delayed or incorrect decisions. Similarly, mis-calibrated trust in automation (~48%) and mode confusion (~47%) indicate instability in human–automation teaming, reinforcing prior findings that inappropriate trust calibration and interface complexity are critical precursors to operational errors in increasingly automated maritime environments.

The observed dominance of communication and team-related variables further highlights the systemic nature of failure propagation. Poor communication quality (63%) and unclear role responsibility (37%) suggest breakdowns in shared mental models, which are known to amplify the impact of individual cognitive limitations under time pressure and fatigue. This aligns with recent studies emphasizing that bridge team coordination and

communication discipline remain central risk controls even in digitally enhanced navigation systems, where over-reliance on automation can obscure role clarity and reduce active cross-checking behaviors. From an operational perspective, these results imply that accident severity is not driven by isolated factors but by interacting clusters of human, system, and environmental conditions, with digital-era failure modes (e.g., alarm ineffectiveness, interface fragmentation, automation bias) acting as key amplifiers. Consistent with recent maritime safety literature, the findings underscore the need for integrated training interventions that simultaneously target cognitive resilience (situational awareness, decision-making under pressure), human–automation calibration, and team communication protocols, rather than addressing these dimensions in isolation.

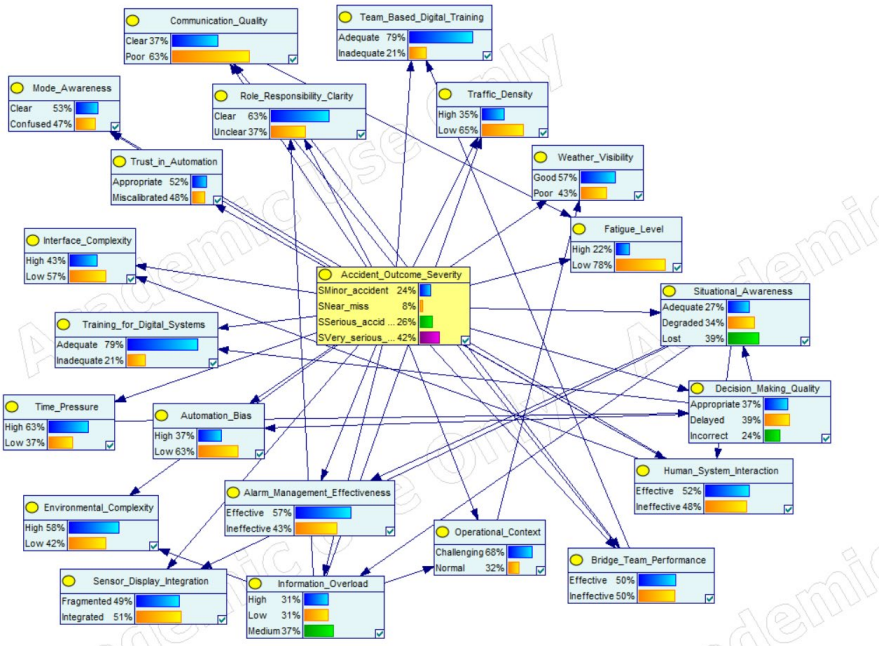


Figure 1. Model prediction analysis

3.2 Model Diagnostic Analysis

The diagnostic results show a clear severity gradient structured around decision quality, situational awareness, and operating context. Conditioning on very serious accidents sharply shifts probability mass toward degraded cognitive states: *Incorrect decision-making* rises (+23 pp), *lost situational awareness* rises (+27 pp), while *appropriate decisions* and *adequate awareness* collapse (−30 pp and −22 pp). At the same time, the *challenging operational context* increases further (+21 pp). This pattern indicates that catastrophic outcomes are not driven by a single failure, but by a coupled breakdown in cognition and context, where demanding operations amplify degraded awareness and poor decisions. For serious accidents, the profile is more mixed. Unlike the very serious state, *appropriate decision-making* increases (+14 pp), while *incorrect decisions* and *lost awareness* fall. Together with small increases in *adequate digital training* and *good visibility*, this suggests that serious outcomes often arise despite partially functioning human and technical controls. In other words, these events remain consequential, but are still somewhat recoverable compared with very serious cases. The near miss profile is effectively the mirror image of catastrophe. Large increases in *normal context* (+44 pp), *appropriate decisions* (+42 pp), *clear communication* (+39 pp), and *low information overload* (+32 pp), combined with a major reduction in *lost awareness* (−37 pp), show that resilient outcomes depend on preserving cognitive margin and team clarity under manageable operating conditions. The minor accident state sits between these extremes, with improved *adequate awareness*, *appropriate decisions*, *normal context*, and *integrated sensor displays*. This implies that minor consequences are associated with partial degradation rather than full breakdown. Overall, the table confirms that severity escalation in digitized maritime operations is chiefly governed by the interaction of awareness, decision-making, operational difficulty, communication, and

information/interface quality, which directly supports training priorities in cognitive resilience and digital bridge management.

Table 2. Tabulated results for the top five factors of each consequence severity scenario in diagnostic analysis.

Evidence	Rk	Factor (state shown)	Prior	Post.	Δ (pp)	Evidence	Rk	Factor (state shown)	Prior	Post.	Δ (pp)
Very serious = 100%	1	Decision_Making_Quality (Appropriate)	37	7	−30	Near miss = 100%	1	Operational_Context (Normal)	32	76	+44
	2	Situational_Awareness (Lost)	39	66	+27		2	Decision_Making_Quality (Appropriate)	37	79	+42
	3	Decision_Making_Quality (Incorrect)	24	47	+23		3	Communication_Quality (Clear)	37	76	+39
	4	Situational_Awareness (Adequate)	27	7	−22		4	Situational_Awareness (Lost)	39	2	−37
	5	Operational_Context (Challenging)	68	89	+21		5	Information_Overload (Low)	31	63	+32
Serious = 100%	1	Decision_Making_Quality (Appropriate)	37	51	+14	Minor accident = 100%	1	Situational_Awareness (Adequate)	27	52	+25
	2	Decision_Making_Quality (Incorrect)	24	12	−12		2	Situational_Awareness (Lost)	39	14	−25
	3	Situational_Awareness (Lost)	39	28	−11		3	Decision_Making_Quality (Appropriate)	37	58	+21
	4	Training_for_Digital_Systems (Adequate)	79	86	+7		4	Operational_Context (Normal)	32	52	+20
	5	Weather_Visibility (Good)	57	64	+7		5	Sensor_Display_Integration (Integrated)	51	68	+17

3.3 Scenario Analysis

The scenario results show a highly coherent severity logic. Scenario 1 produces the strongest escalation, with 73% probability of very serious outcomes, indicating that severity rises sharply when operational stressors are stacked simultaneously. The pattern suggests that contextual stress does not merely add risk; it degrades the human-performance envelope by shifting probability mass toward lost situational awareness, delayed/incorrect decisions, ineffective bridge performance, and degraded HSI. This reflects a classic compound-failure pathway in which communication breakdown, high time pressure, and adverse conditions jointly reduce detection, coordination, and recovery capability. Scenario 2 yields a similarly severe profile (71% very serious), but through a more specifically digital pathway. Here, fragmented displays, mode confusion, mis-calibrated trust, and ineffective alarms induce the strongest degradation in HSI (89% ineffective) and situational awareness (75% lost). The results imply that digital-system failures propagate into cognition and team performance rather than remaining isolated interface problems. In other words, poor automation design and trust mismanagement function as severity amplifiers by disrupting operator comprehension, prioritization, and response timing. By contrast, Scenario 3 effectively suppresses catastrophic outcomes (0% very serious) and concentrates probability in minor (45%) and near miss (38%) states. This shows that resilience is not defined by one protective factor alone, but by a reinforcing cluster: normal context, effective HSI, adequate awareness, and appropriate decisions. The induced shifts toward low traffic, good visibility, effective alarms, integrated displays, and low overload suggest that stable human–system coordination preserves cognitive margin and prevents escalation. Collectively, these scenarios confirm that accident severity in digitized maritime operations is governed by interacting bundles of context stress, cognitive degradation, and digital interaction quality, which directly supports integrated training and interface design interventions.

Table 3. Evidence details and prominent trends in scenario analysis

Scenario	Evidence set	Posterior severity (%)	Most prominent induced states
S1: High-risk operational stack	Challenging context; poor weather/visibility; high time pressure; poor communication	Very serious 73; Serious 17; Minor 9; Near miss 0	SA: Lost 57%; Decision Making (DM): Delayed/Incorrect 84%; Bridge ineffective 72%; HSI ineffective 56%; Environmental complexity high 66%; Sensor display fragmented 60%
S2: Human–system breakdown	Fragmented displays; mode confusion; mis-calibrated trust; ineffective alarms	Very serious 71; Serious 21; Minor 8; Near miss 0	SA: Lost 75%; HSI ineffective 89%; DM: Delayed/Incorrect 84%; Operational context challenging 82%; Communication poor 69%; Interface complexity high 65%; Environmental complexity high 68%
S3: Resilient near-miss signature	Normal context; effective HSI; adequate SA; appropriate DM	Minor 45; Near miss 38; Serious 17; Very serious 0	SA adequate 100%; DM appropriate 100%; HSI effective 100%; Weather good 82%; Traffic low 90%; Alarm management effective 87%; Sensor display integrated 80%; Information overload low 72%

4. Conclusions

Maritime transport is undergoing rapid digitization. Though this facilitates maritime transport, however, it enhances the complexities for the involved crews, specifically under challenging conditions. Despite this, human reliability under these intricate digitized systems remains scarcely explored. This study presents a data-driven, human-centered BN framework for quantifying accident outcome severity in digitized maritime operations. By systematically translating qualitative accident investigation evidence into a probabilistic model, the approach captures the interacting effects of cognitive performance, human–system interaction, team coordination, and operational context. The TAN-BN showed strong predictive reliability across all four severity states, with AUC values ranging from 0.835 to 0.967, confirming its suitability for severity classification and inference in digitized maritime operations. The marginal distribution of *Accident_Outcome_Severity* indicates a dominance of Very serious (42%) and Serious (26%) outcomes, with comparatively lower probabilities for Minor (24%) and Near miss (8%), suggesting that once adverse conditions emerge, the system tends to escalate toward higher consequence states rather than remain benign. The results consistently show that severity escalation is governed by coupled degradation in situational awareness and decision-making under challenging conditions, further amplified by digital interaction failures such as fragmented displays and mis-calibrated trust. Conversely, resilient outcomes emerge from aligned human–system performance, effective communication, and manageable operational contexts. The model demonstrates strong predictive capability and provides interpretable insights that directly support training and operational design. Importantly, it enables identification of critical leverage points for intervention, emphasizing integrated training in cognitive resilience, human–automation calibration, and bridge team coordination. This framework offers a practical pathway for developing competency-based, safety-critical training aligned with the demands of increasingly digital maritime systems.

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Eye-Tracking in Maritime Operations: A Review of Existing Research

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Abstract: The application of eye-tracking technologies in the maritime context is increasingly being considered as a tool for better understanding the behaviour and workload of seafarers during complex operational tasks. In the literature, eye-tracking is applied in research on navigation, engine room work, and seafarer training and education, but the approaches and research objectives of these studies vary considerably. This paper reviews studies indexed in Scopus that address the application of eye-tracking technologies in maritime operations and education. The search and selection of relevant papers were done in accordance with the PRISMA guidelines. The titles and abstracts of the identified papers were screened to identify whether the research is relevant to maritime operations and training. The included studies were qualitatively analysed according to field of application, experimental environment (simulator or real ship), and the eye-tracking metrics used. The paper aims to provide an overview of how eye-tracking technologies are applied in the maritime context and to identify directions for future research. Therefore, this paper provides guidance on the use of eye-tracking as a tool to improve safety at sea and to better understand the role of the human factor in critical and routine operations aboard ships.

Keywords: eye-tracking; maritime simulator; maritime training and education; human factors; maritime operations

1. Introduction

Maritime operations are characterised by high levels of complexity and demanding operational conditions, resulting from the interaction of human, technical, and organisational factors within dynamic and congested operational environments (Adumene et al., 2022; Crestelo Moreno et al., 2022). Despite continuous advancements in ship design, navigation equipment, and safety regulations, accidents at sea still occur. The human factor remains one of the dominant contributing elements (Hasanspahić et al., 2021). Previous research consistently indicates that human actions play a significant role in maritime accidents, often due to reduced situational awareness, fatigue, and poor decision-making under operational stress (Kartoglu et al., 2022; Russo et al., 2022; Zhang et al., 2025). Furthermore, technology-induced human error, developed by the ineffective relationship between operators and technology, for example, inadequate ECDIS usage, plays a significant role in maritime accidents, especially groundings (Bielić et al., 2017; Turna and Öztürk, 2019). In this context, gaining insight into human behaviour during shipboard operations has become a key focus in maritime safety studies. Traditional methods for assessing human factor contribution, such as subjective workload scales or post-incident reviews, typically depend on self-reporting and retrospective interpretation (Stanton et al., 2013). As a result, there is an increasing need for objective methods capable of capturing real-time cognitive and behavioural processes during maritime operations.

Eye-tracking is one approach used to analyse human performance. Recording eye movements, including fixation patterns, saccades, pupil diameter and gaze distribution, allows direct observation of how operators allocate visual attention and process information in complex environments (Mahanama et al., 2022; Qian et al., 2025). These metrics can be used to assess cognitive workload, situational awareness, and fatigue and are applied in the analysis of human–system interaction in safety-critical domains (Zhang et al., 2025). Eye-tracking is widely used in fields such as aviation, road transport and medicine (Martínez-Marquez et al., 2021; Heikoop et al., 2017; van der Gijp et al., 2017), but its application in the maritime domain remains limited and methodologically fragmented (Kamarumtham et al., 2026). Existing maritime studies have applied eye-tracking

across a range of contexts, including navigation and simulator-based training (Kamarumtham et al., 2026). However, these studies differ significantly in their research objectives, experimental designs, and the selection of eye-tracking metrics, which makes comparison and synthesis of results challenging.

Recent studies focus on several main areas of eye-tracking application in maritime research. These include mental workload assessment, gaze pattern analysis, training evaluation, human–machine interaction and fatigue detection (Kamarumtham et al., 2026). Differences are consistently observed between maritime experts and trainees. Experienced seafarers are showing more efficient visual scanning patterns and rely less on instruments than trainees (Chen et al., 2025). Pupil diameter is also used as an indicator of fatigue in navigational tasks (Zhang et al., 2025). Furthermore, most existing studies are conducted in navigation simulators, usually with small samples, while usage on real ships during operations remains very limited (Ma et al., 2024; Kamarumtham et al., 2026). This is a key limitation, as simulator settings cannot fully reproduce operational conditions such as time pressure, crew interaction and real consequences of decisions. As a result, observed visual behaviour may not reflect actual seafarers' behaviour at sea. In addition, there is no consistency in the use of eye-tracking metrics, which makes comparison difficult and limits the practical applicability of the results (Kamarumtham et al., 2026).

Although eye-tracking is increasingly used, its application in maritime safety research and practice is still at an early stage. This paper provides a systematic review of studies indexed in Scopus following the PRISMA 2020 methodology (Page et al., 2021) and examines the use of eye-tracking in the maritime context. The selected studies are analysed and classified according to the application area, the experimental environment (simulator or real ship), and the gaze-tracking metrics used. The focus is on how eye-tracking is applied, not on general descriptions of the technology. The analysis considers where the studies are conducted, what is measured (situational awareness, workload, fatigue), and whether eye-tracking is combined with other methods. This shows which approaches dominate and where they differ. The paper identifies gaps in the literature, including the lack of real ship validation, inconsistent use of metrics and limited coverage of certain operational domains. The contribution of this paper is a clearer picture of current practice and its limitations, rather than a new methodological approach.

2. Methodology

The literature search was done using the Scopus database. Keywords related to eye-tracking and the maritime domain were combined using Boolean operators ("eye tracking" OR "eye-tracking" AND "maritime", "ship", "navigation", "bridge", "engine room", "seafarer", "marine", "vessel"). The search was limited to peer-reviewed journal articles and conference papers published in English. Studies were included if they applied eye-tracking in a maritime context (e.g. navigation, engine room, MET) and were based on empirical or experimental data. Only studies using eye-tracking metrics (such as fixation duration, saccades and scanpaths) and addressing human factors, workload, situational awareness or performance were considered. Studies not related to the maritime domain, without eye-tracking, focused solely on technical systems, or lacking empirical data were excluded.

The selection was carried out in three steps: identification, screening and eligibility assessment. Titles and abstracts were reviewed first, followed by full-text analysis. For each study, the application domain, experimental environment, eye-tracking metrics, research objective and key findings were extracted. The analysis was qualitative, with studies grouped by operational domain, research setting, and metric type. This allowed the identification of common approaches as well as gaps in the literature.

3. Results

A total of 158 records were screened. After applying the inclusion and exclusion criteria, 31 studies were included in the final review, while 127 were excluded (Figure 1). The largest exclusion group consisted of studies not related to the maritime domain (n = 94), followed by studies that did not include eye-tracking (n = 28).

The 31 included studies were published between 2015 and 2026. The largest number of studies was published in 2025 (n = 7) and 2024 (n = 7), followed by 2026 (n = 5). In total, 19 of the 31 included studies were published between 2024 and 2026. Most studies were empirical (n = 27), while four were review papers

(Table 1). Simulator-based studies clearly dominated, with 18 conducted primarily in simulator settings; three used video- or laboratory-based designs; four used mixed settings; and only two used real-world operational settings. Four studies included a real-world component in any form (e.g., a real ship, VTS, in-water testing, or operational validation). In terms of primary focus, nine studies addressed situational awareness, cognition, or perception; seven focused on workload, fatigue, or vigilance; five on training, competency, or education; four were review papers, and six covered other applied topics such as usability, augmented reality, robotics, collaboration, and cybersecurity.

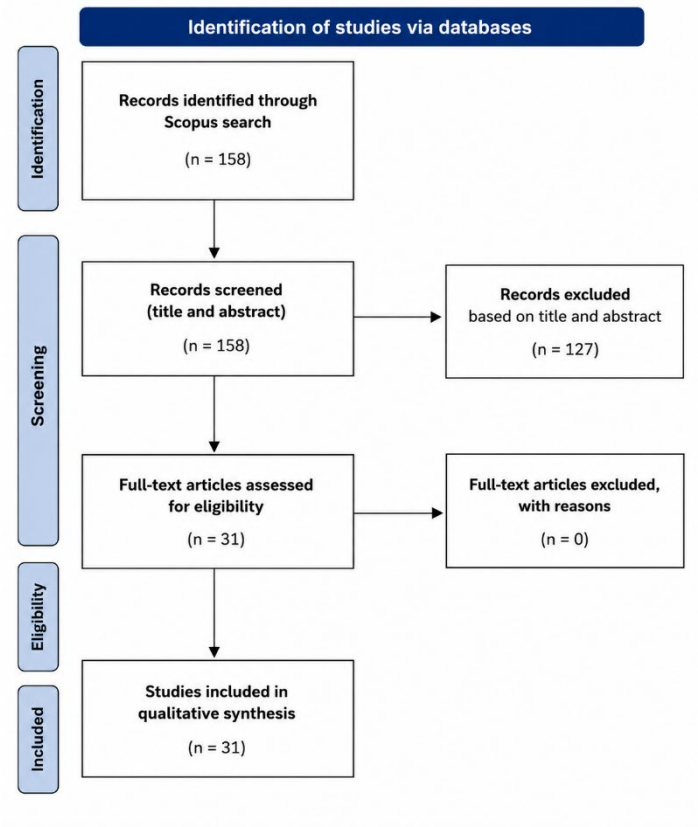


Figure 1. PRISMA flow diagram of the study selection process

Table 1. General characteristics of included studies (n = 31)

Dimension	Category	n (%)
Paper type	Empirical papers	27 (87.1)
	Review papers	4 (12.9)
Primary setting	Simulator-based	18 (58.1)
	Video/laboratory-based	3 (9.7)
	Real-world operational	2 (6.5)
	Mixed setting	4 (12.9)
	Review papers	4 (12.9)
Primary focus	Situational awareness/cognition/perception	9 (29.0)
	Workload/fatigue/vigilance	7 (22.6)
	Training/competency/education	5 (16.1)
	Reviews/synthesis	4 (12.9)

Other applied topics (usability, augmented reality, robotics/control, collaboration, and cybersecurity)	6 (19.4)

Eye-tracking is predominantly used as part of a combined measurement approach. Only a limited number of studies utilised eye-tracking as a standalone method, while most combined it with at least one additional data source. These include physiological measurements (e.g. EEG, heart rate variability), subjective workload scales, communication analysis, and performance-based indicators. This pattern is consistent across domains and does not depend on the research objective. Fixation-based metrics and AOI analysis are used in nearly all studies and represent the baseline analytical approach. These are primarily used to quantify attention distribution and information acquisition. Saccadic behaviour and pupil-related measures are mainly used in studies addressing workload, fatigue, and vigilance. Their use is less consistent, and thresholds or interpretation criteria vary between studies. Seven studies apply machine learning or deep learning models, mainly for classification tasks (e.g. workload level, vigilance state, activity recognition). These approaches rely on higher-dimensional feature sets derived from eye-tracking data, often combined with additional inputs.

The distribution of studies shows a clear imbalance between controlled and operational environments. Most existing studies are done on simulators (58%), while the real shipboard environment is seldom used (7%). Even when mixed designs are included, the number of studies with any operational validation remains low (n = 4). This means that most findings are derived from controlled conditions. The focus is mainly on navigation-related human factors. Situational awareness, workload, and fatigue account for 16 of 31 studies (51.6%), while other operational domains, such as cargo operations, engine room activities, and shipboard coordination, are only marginally represented. Eye-tracking is most often used to distinguish between operator states and performance levels. Experienced operators show more focused gaze patterns, shorter fixation durations and more task-relevant visual allocation, while less experienced participants show more dispersed gaze behaviour and greater reliance on instruments. Changes in workload and fatigue are reflected in pupil diameter and fixation-based measures, but the results vary depending on the experimental design and measurement approach. Multimodal approaches are dominant in maritime eye-tracking research. A total of 22 out of 31 studies (71.0%) combine eye-tracking with other data sources, showing a shift towards integrated assessment of operator state rather than isolated gaze analysis. Machine learning approaches are present but still limited (n = 7; 22.6%). Although these studies report high classification accuracy, they are mostly based on small samples and controlled conditions, which limit their findings.

Most studies are still based on simulators, while real-world data is very limited, so the applicability of the results to real operations remains questionable. Also, it is important to note that the sample sizes (number of participants) in the reviewed studies are relatively small, thereby reducing the robustness of the results. There is also a lack of consistency in the use of eye-tracking metrics. Some critical shipboard operations where the human factor plays an important role are still inadequately included, especially cargo operations, engine room tasks, and more complex team environments.

4. Discussion

Most studies rely on simulator work (Chen et al., 2025; Jiang et al., 2021; Ma et al., 2024; Sharma et al., 2024; Atik and Arslan, 2019; Atik, 2020). Real ship operational conditions are rarely used in the reviewed studies (Orlandi and Brooks, 2018; Pan et al., 2018; Kamarumtham and Murai, 2025a), which could be considered a limitation. It is important to emphasise that seafarers' visual behaviour depends on real maritime surroundings, task dynamics, and interactions between operators. These conditions are not captured in simulator settings. In real bridge operations, attention is distributed across multiple sources, including surrounding traffic conditions, weather conditions and external/internal communications and system alarms, and is continuously influenced by concurrent tasks and interruptions. As a result, gaze patterns observed in simulator studies tend to be more stable than in real operations. Without validation in real ship conditions, it is not entirely clear whether this data reflects the subjects' actual behaviour or is a result of the way the experiment was set up.

The reviewed studies are mainly focused on the human factor in marine navigation, including the effects of situational awareness, workload, and fatigue (Virdi et al., 2022; Zhang et al., 2025; Ma et al., 2024; Li et al., 2024; Hung et al., 2026). Workload increases with task complexity, especially in time-critical conditions such

as collision avoidance. Experience at sea also plays a consistent role, with more experienced seafarers showing more efficient visual behaviour, shorter fixation durations and more structured gaze patterns, while less experienced ones show longer fixations and more dispersed attention under complex conditions (Hung et al., 2026).

Eye-tracking is mostly used to analyse visual attention and information processing. The most frequent metrics include fixation duration, fixation count and AOI measures (Arslan et al., 2021), which indicate where attention is directed and how it is distributed. It is also important to note that visual attention does not necessarily correspond to cognitive processing. Looking at a particular object does not mean that the operator has recognised or understood the available information. Similarly, relevant information may be perceived without direct visual fixation. Therefore, eye-tracking metrics should be interpreted as indirect indicators of operator state rather than direct measures of situational awareness or decision-making. However, these metrics assume relatively stable attention. In real marine environment navigation, attention shifts frequently and is often driven by ship surroundings and other inputs, such as bridge alarms and GMDSS communication, which reduces its applicability in dynamic situations. Although these could be relatively well simulated, the perception of the simulator as a "safe environment" where no harm can be done remains, thus affecting participants' behaviour and decision-making.

AOI-based approaches are also used to assess navigation system usability, where interface design influences visual search behaviour and task performance (Arslan et al., 2021). Saccade metrics are used less frequently, mainly to analyse transitions between information sources, and their definitions vary across studies. Pupil diameter is commonly used to assess workload and fatigue (Zhang et al., 2025; Orlandi and Brooks, 2018). A limitation of pupil-based measurement is its sensitivity to external factors, such as lighting and stress, which makes interpretation difficult outside controlled environments. This complicates interpretation in real operational environments. Another important limitation is the lack of standardisation in the use of eye-tracking metrics. Differences in preprocessing procedures, AOI definitions and interpretation criteria make direct comparison between studies difficult. Consequently, the available evidence remains fragmented and more robust conclusions across studies are difficult to establish.

Differences between experience levels are clearly visible in eye-tracking data (Petrović and Vujičić, 2025; Eklund et al., 2020; Kamarumtham and Murai, 2024; Kamarumtham and Murai, 2025b). More experienced operators exhibit more structured, efficient gaze behaviour, whereas less experienced participants show more scattered attention patterns. Differences between expert and novice operators are consistently observed, but these differences are amplified in simulator settings where task structure is simplified. Although simulator studies provide controlled and repeatable experimental conditions, they cannot fully replicate the operational complexity of real shipboard environments. As a result, the observed gaze behaviour may be influenced by the experimental setting itself. Consequently, differences between experienced and less experienced operators should be interpreted cautiously, as they may not fully represent visual behaviour during actual ship operations. Similar differences appear in studies using bio-signals, where experienced pilots show higher levels of situational awareness compared to students. Training studies show the same pattern (Atik and Arslan, 2019; Chen et al., 2025; Sharma et al., 2024). Eye-tracking is also combined with questionnaires and sentiment analysis to assess user satisfaction and usability of training systems, including ECDIS and simulators (Papachristos and Nikitakos, 2016). In most cases, however, eye-tracking is still used at a descriptive level.

More recent studies move towards multimodal approaches (Kurt et al., 2026; Ma et al., 2026; Kamarumtham and Murai, 2025a). Eye-tracking is combined with physiological data, behavioural indicators and performance measures. This gives a more complete picture, but also introduces variability, since there is no standard way to combine these data. The reliance on multimodal approaches reflects the limitations of eye-tracking as a standalone method, particularly in complex operational environments. The increasing use of multimodal approaches indicates that eye-tracking alone is unlikely to provide a sufficiently reliable assessment of operator state. Instead, it appears to be most useful when combined with physiological and behavioural measures, allowing a more comprehensive evaluation of human performance during maritime operations. Future studies should therefore focus on integrated rather than standalone eye-tracking approaches. In addition, machine learning approaches are increasingly used (Virdi et al., 2022; Ma et al., 2024; Jiang et al., 2024; Kamarumtham and Murai, 2025b). Eye-tracking data are used as input for classification models, where fixation, saccade and derived features are used to detect cognitive states, including low situational awareness. The high

classification accuracy reported in these studies should be interpreted with caution, as models are typically trained on small, highly controlled datasets. This limits their generalisability to real operational settings.

Other applications exist, but they are still limited. This includes human–machine interaction, augmented reality and communication (Barth et al., 2025; Mallam et al., 2024; Pan et al., 2018). These studies are mostly exploratory and not yet consistent in approach. There are also examples outside the main research focus, such as cybersecurity (Wolsing et al., 2022), collaboration and team interaction (Streilein et al., 2020) and general application studies (Uflaz et al., 2023). These show that the field is expanding, but still fragmented.

Review papers show the same pattern (Kamarumtham et al., 2026; Qian et al., 2025; Zhou and Munim, 2025; Mišlov et al., 2024). Eye-tracking is widely used, but there is no consistent approach to how metrics are applied or interpreted. Most studies rely on fixation and AOI measures, while saccades and pupil-based metrics are used less systematically. Definitions, preprocessing, and analysis differ across studies, and therefore results are difficult to compare. Most studies presented are based on simulator work, limiting their applicability in real ship operations. Without validation in real conditions, it is not clear whether these metrics reflect actual behaviour. This is a key limitation, especially if eye-tracking is to be used for operational decision-making.

5. Conclusion

Eye-tracking represents a useful tool for improving maritime safety. It has the potential to upgrade learning processes and facilitate research in human error at sea. Furthermore, as the era of autonomous shipping approaches, eye-tracking could be useful for developing training programs for future operators.

The study found that most eye-tracking studies in the maritime context are developed using simulators. However, experiments or validation, including real conditions (real ships), are rare. This fact leads to the conclusion that, although the simulators are excellent tools for practising and learning, a simulated environment might affect the results because the dynamics and decision results of the real world are difficult to achieve. Therefore, it is not clear how well the results apply in real conditions at sea. Moreover, the reviewed studies focus on marine navigation. Other maritime tasks are mostly ignored, including cargo and engine room operations, where the human factor plays a decisive role in safety outcomes. To fill these gaps, future studies should address other maritime tasks where human factors are critical and use the real ship environment for validation. In addition, eye-tracking in the maritime context is primarily used to analyse visual attention and operator states, often in combination with other methods. However, there is no consistency in metrics. This makes comparison between studies difficult. Addressing these gaps would improve the applicability of eye-tracking in maritime safety research and support its wider use in practice.

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The impact of the post-COVID world on the containerized cargo turnover in the East Mediterranean and Black Sea area

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Abstract: The expected steady progress in global development after the COVID-19 pandemic, sadly, did not happen, as new military conflicts broke out and political events grew unstable. These issues pushed the already weak world economy into bigger challenges. The effects stood out most in the East Mediterranean Sea and Black Sea region. This research analyses the main trade routes in these regions. It explains how global politics have changed the shipping industry, with focus on container trade. We have studied data on cargo volumes and ship traffic in order to pinpoint the most influential factors at play. It also shows the steps the industry has taken in response, aiming to keep trade routes open and extra shipping services active. For this research, we have used the VesselFinder software for tracking ships and analysing their paths. We have relied on the Player function for replays and Voyage Analyser for deep reviews. With these tools, we processed and studied an archive of container cargo traffic over the past four years in the researched area.

Keywords: containerized cargo turnover; East Mediterranean and Black Sea area; Red Sea and Black Sea crisis

1. Introduction

When COVID-19 was coming to an end, at the beginning of 2022, humanity was hoping that life would return to normal and the world would continue its steady development. Unfortunately, several military conflicts, as well as turbulent political events, have pushed the still fragile world economy into new and bigger challenges, the effect of which has been even more evident in the area of the Eastern Mediterranean Sea and Black Sea. Moreover, when analysing in depth, one may find that major events happened much earlier, shaping the trading reality that all parties in the area are now experiencing. Our research aims at finding the origins of the problem, hoping to assist in mitigating the effect.

The first major turmoil was the unpredicted Russian-Ukrainian conflict, which is still shaping the sea trade environment of the region. The frequent reports of sea mines, floating in Black Sea waters, together with recent events of drone attacks on ships believed to be part of the Russian shadow fleet, have made seaborne cargo turnover in neighboring countries drop significantly, instead of the expected post-COVID increase. The combination of the high-risk visits to the Black Sea, together with ever-growing expenses for entering the area, makes operators further reluctant to trade in these particular seas. The problem is still far from the solution that all Black Sea countries have been hoping for.

The second major event was the unprecedented attack on Israel by the Hamas movement, which in turn led to the eruption of the Gaza war and “Red Sea crisis”. (Pedrozo, 2025) “Red Sea crisis” is the name adopted for the military actions of the radical Islamic group of Ansar Allah, also known as Houthis, in solidarity with the Palestinian people in Gaza. As a result, all seaborne trading endeavors, believed to be in some way connected to Israel, were targeted. According to official statistical data, nearly 100 vessels have fallen victim to Houthis’ actions, which involve hijacking (like the case of m/v Galaxy Leader), missile, and even drone attacks. These highly organized attacks led to the withdrawal of most seaborne carriers from the Red Sea and Suez route. As a result, most port calls in the East Mediterranean area have dropped significantly (Delivorias, 2024). The vessels were rerouted around the Cape of Good Hope, and despite significantly higher rates and longer transit times, port calls increased in the western part of the continent, leaving most transhipment hubs in the East without significant trade.

The Black Sea region was also affected by the change of Bosphorus and Dardanelles straits' transit charges, increased by 15% by July 1-st, 2025. This event, combined with high-risk conditions of the Black Sea, has further contributed to the sharp drop in seaborne cargo turnover in the area (Partene et al., 2023).

The present research aims to examine the available statistical data for the main trading routes in the East Mediterranean Sea and Black Sea, showcasing how recent events have affected the shipping industry, particularly in the container trade. We examine the most significant factors and the steps taken by the industry in its effort to maintain the trading routes and the additional shipping services active. For the purposes of the study, specialized software (VesselFinder - www.vesselfinder.com) was used to track and analyse vessel traffic. An archive of containerized cargo traffic for the last four years in the area of interest was processed and analysed by using its built-in functions for playback (Player- www.player.vesselfinder.com) and analysis (Voyage Analyser - www.voyage.vesselfinder.com). The archive contains data from ship AIS transponders and includes ship identification and type, position, destination, and ETA (Sotirov and Alexandrov, 2017). (See Figure 1).

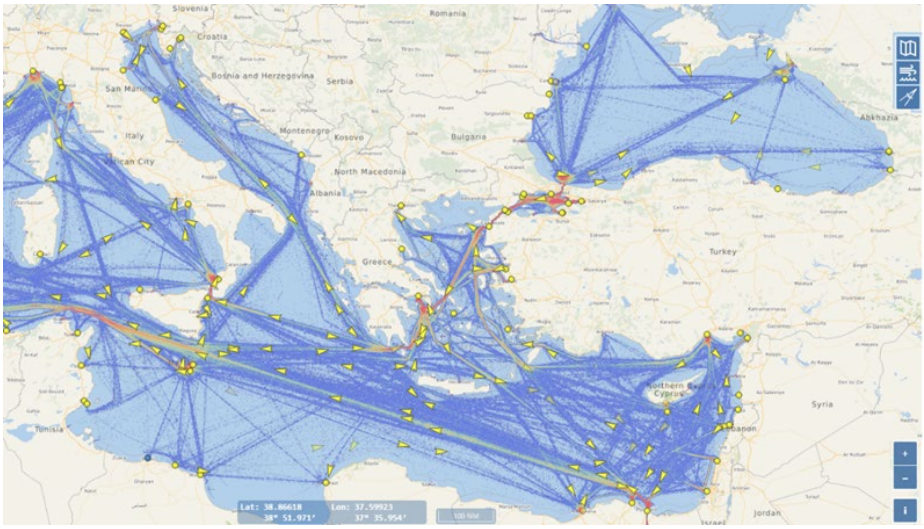


Figure 1. A screenshot of Voyage Analyser application used to analyse the traffic of containerships in the area of interest.

2. Features of the container trade in the Black Sea area in the period 2005 - 2026

In the period of 2005-2010, there was a notable increase in maritime trade in the area, following acceptance of Bulgaria and Romania in the EU. According to data from www.georank.com, both countries saw a growth of their GDP per capita of almost 50% for the period. Although the effects of the economic crisis of 2008 – 2010 resulted in reduced growth, they did not cause a significant stall of maritime trade. The first events to have major negative impact were the Maidan or the Ukrainian Revolution of early 2014 and the subsequent occupation of Crimea by Russia. They lead to lasting military conflict between Russia and Ukraine, one that is still active to this day. Furthermore, this situation caused stagnation of Ukrainian economy and the country's GDP was reduced by more than 6% (Klymenko et al., 2020). The effect on international trade was immediate, the first sanction rules against Russia were introduces by the EU, limiting trade and financial connections between EU countries and Russia. As a countermeasure, Russia also introduced trading restrictions, particularly on foodstuffs. This changed significantly the trading pattern of the region, particularly in Bulgaria, as there were longstanding traditions and established connections between Russia and Bulgaria. This result was evident in the entire region. A study on the Black Sea region, published in 2016 by portstrategy.com showed a sharp 14% drop in the laden container turnover for the period 2014 – 2016. As a result, some of the newly developed services, entering the Black Sea ports, decided to reroute and to use feeder system for ports inside Black Sea basin (Sumer, 2015). A vivid example is the Grand Alliance Asia-Black Sea service which was introduced in 2007, calling both Constanta and Odessa, which did not succeed in acquiring a share and rescheduled in 2009, following the financial crisis, with hope to return to normal function. However, the Grand alliance was later restructured and member lines became part of other ventures. As a result, and following all political and military turmoil, the grand alliance lines have no interest in entering the port, leaving local trade to be delivered by local

feeders. And this is not the only example. Even with these major setbacks, there was a rise in container trade, particularly triggered by rise of the Ukrainian economy in 2017.

The next significant event was the COVID-19 crisis. However, as it was not a local event, its effect was felt all over the world. There were a number of support measures, particularly by EU. However, by no doubt, the stagnation in international trade was evident. Unfortunately, as in 2022 the world was becoming more and more optimistic regarding the economic recovery from COVID-19, two very significant events reshaped container traffic in the region of Black Sea and Eastern Mediterranean. First, there was the open military conflict between Ukraine and Russia. The results from this event, still ongoing to this day, were not purely economical for other Black Sea countries.

The most obvious initial result was the blockade of several Ukrainian ports, including Odesa, Kherson, and Mariupol, and constant bombardments in the first days of the conflict, as well as subsequent mining of port entrances. Even if there were no container vessels stranded in these ports, there were several other types of ships blocked there. Another direct effect was the obvious significant fall in trade in Novorossiysk. The entire region of the Black Sea and the Azov Sea is now considered a war-like area, which significantly increases the expenses of calling ports in the area (see Figure 2). In addition, the numerous reports of floating mines, originating from mined waters of the conflict, further increased tension in shipping companies.

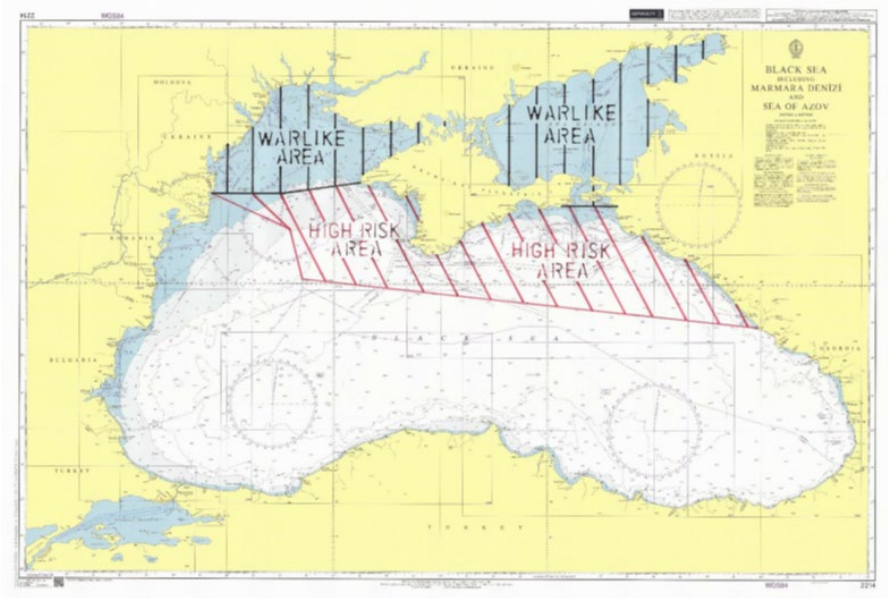


Figure 2. War like area in Black Sea and Azov (source IBF).

The result was the introduction of a number of sanctions against Russia, which brought further withdrawal of Russia from trading with the EU, tension in the energy sector, and, most recently, an increase in drone attacks on ships in Black Sea basin. (Klymenko et al., 2020). Even with attacks only on dark fleet ships, the drones created additional tension, and all container lines decided to effectively withdraw from direct Black Sea trade (Yetkili et al., 2015).

The analysis we have completed is based on inbound and outbound traffic of container carriers in and out of the Black Sea basin (Bosporus traffic) and the eastern med (Suez Canal in and out traffic), with data for the period 2022-2025 (Delivorias, 2024). We have noticed there was no significant difference in the traffic of container vessels of the mentioned period, so we had to look elsewhere to explain the situation. We have realized that the most significant diminishing of container vessel traffic had already happened in the period 2014 – 2016, backed by the COVID crisis.

All the remaining traffic is fully operated by the Arkas line, the Unifeeder line, and the dedicated feeder of the MSC. We have annualized the most recent traffic of vessels entering the container terminal at Varna port for April 2026, shown in Figure 3. The vessels entering the port terminal are the ones serving Arkas (m/v Admiral Moon), Unifeeder (m/v Nina A, m/v Moraga), and the MSC dedicated line (m/v Gozde Bayraktar).

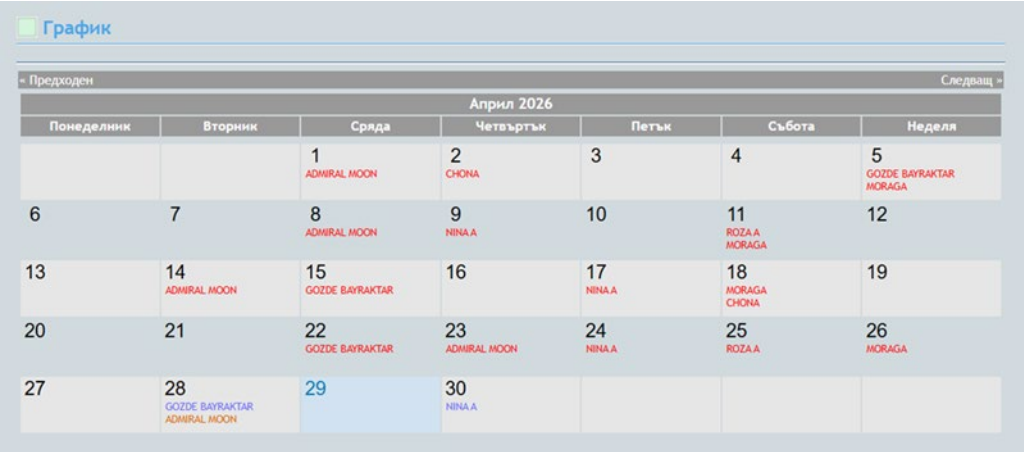


Figure 3. Schedule of the Varna container terminal for the month of April 2026 (source www.port-varna.bg).

3. A chronological overview of container shipping trade in the East Mediterranean and Red Sea regions from 2001 to 2026.

In 2001, the Suez Canal established its baseline for container traffic, with containerized cargo at approximately 144 million tonnes, reflecting the 2000 level. Between 2000 and 2008, cargo passing through the Suez Canal doubled, driven primarily by growing trade from Asia and the Arabian Gulf. By 2002, containerized shipments at Middle East and North Africa (MENA) ports began a strong growth trajectory, expanding by 67% from 2002 to 2008—more than double the 33% growth seen in North America during the same period.

A major milestone occurred in October 2004 with the opening of the Port Said Suez Canal Container Terminal (SCCT). This facility, with a capacity of 5.4 million TEUs, was established as a transhipment center for the Eastern Mediterranean and is operated under concession by APM Terminals. Between 2004 and 2008, Eastern Mediterranean ports developed as key transhipment hubs linked directly to the growing Suez Canal traffic.

Container vessel transits through the Suez Canal surged during this period. By 2008, 8,156 container vessels transited the canal – a 74% increase compared to 2001. More than one-third of all vessels passing through were container ships, and approximately 50% of eastbound cargo was containerized. In 2008, roughly 723 million tons of cargo passed through the Suez Canal, nearly double the 2001 tonnage, with nearly half of this volume being containerized. Containerized cargo alone reached 344 million tonnes, a 139% increase from 2000 (Notteboom and Rodrigue, 2011).

The year 2008 also marked Mersin (Turkiye) emerging as a major Eastern Mediterranean container hub. Mersin's container volumes quadrupled between 2001 and 2011, with an average annual growth rate of 6.0% from 1984 to 2011. However, the global financial crisis of 2008–2009 caused a sharp contraction in global container trade, negatively affecting Suez Canal and East Med/Red Sea routes. Recovery began in 2010, when shipping traffic and tonnage on the Suez Canal increased, signalling a recovering global economy. MENA container ports also resumed their growth trajectory after the 2008–2009 contraction (Merk, 2014).

Mersin continued its strong growth trajectory, with an average container growth rate of 7.3% annually between 2005 and 2011, virtually undisturbed by the 2008 crisis. During 2011–2019, Asia dominated global container flows, accounting for 64% of global container port traffic, while Europe held 16%, North America 8%, and Africa 4%. The Eastern Mediterranean port economy continued expanding throughout this period, benefiting from Asia-Europe trade routes via the Suez Canal (UNCTAD, 2024).

The COVID-19 pandemic caused major disruptions to global container shipping during 2020–2021, including port congestion and capacity issues that affected all routes. A strong post-pandemic recovery occurred in 2021–2022, with container trade rebounding strongly. The East Med and Red Sea routes benefited from this Asia-Europe recovery.

In 2023, the pre-crisis baseline for Suez Canal capacity on the Asia-Europe route was 4.1 million TEUs per month. In late 2023, Houthi rebels launched sustained attacks on commercial vessels in the Red Sea and Bab el-Mandeb Strait, causing container traffic through Bab el-Mandeb to plunge sharply. Carriers began

diverting around the Cape of Good Hope, adding approximately 11,000 nautical miles and 10–14 days longer transit times. Freight rates on Asia-Europe corridors soared as a result (GLOBAL TRADE MAG, 2026).

Throughout 2024, sustained Houthi attacks kept Red Sea traffic minimal. Most Asia-Europe container traffic continued the Cape of Good Hope rerouting. By 2025, the monthly average capacity through the Suez Canal dropped to just 292,000 TEUs – a 93% decline from 2023's 4.1 million TEUs. The Red Sea and Bab el-Mandeb container traffic remained severely depressed, and the Cape diversion added significant costs. However, in late 2025, Maersk completed the first successful Red Sea transit since the hostilities outbreak, marking the first sign of a strategic shift from avoidance to cautious experimentation (Container News, 2026).

By early 2026, major carriers began reinstituting Suez Canal services, and Red Sea container shipping gradually returned after the prolonged disruption. In mid-February 2026, the ME11 service resumed transits via the Red Sea and Suez Canal, with westbound and eastbound sailings scheduled under close monitoring. Despite this progress, traffic remained significantly depressed in February 2026. East-to-west shipments via the canal reached only 18.7%, compared to approximately 80% before the disruption. Offered capacity remained well below historical levels, and schedules were not yet fully predictable. However, there was a continued reduction in Houthi attacks on maritime shipping.

Long-term contract rates for shipments from the Far East to North Europe and the Mediterranean fell to the lowest levels since the pre-crisis period, with some new rates even below prevailing spot market levels. In March 2026, global container shipping rates stabilized as the impact of Red Sea rerouting began to normalize and vessel capacity adjusted across key trade lanes. Analysts cautioned that any resurgence of Middle East hostilities could quickly derail this progress and force another round of rerouting.

The Red Sea corridor accounts for 12–15% of global trade, with up to one-third of East-West container flows transiting this route. The Cape of Good Hope diversion added approximately 10–14 days longer transit times, significantly inflating fuel consumption and voyage costs. By 2026, the market began shifting from crisis conditions toward a more competitive environment, with partial reopening exerting downward pressure on rates. The shift in the number of container vessels passing through the Suez Canal during the period of the Red Sea crisis is most evident in Figure 4.

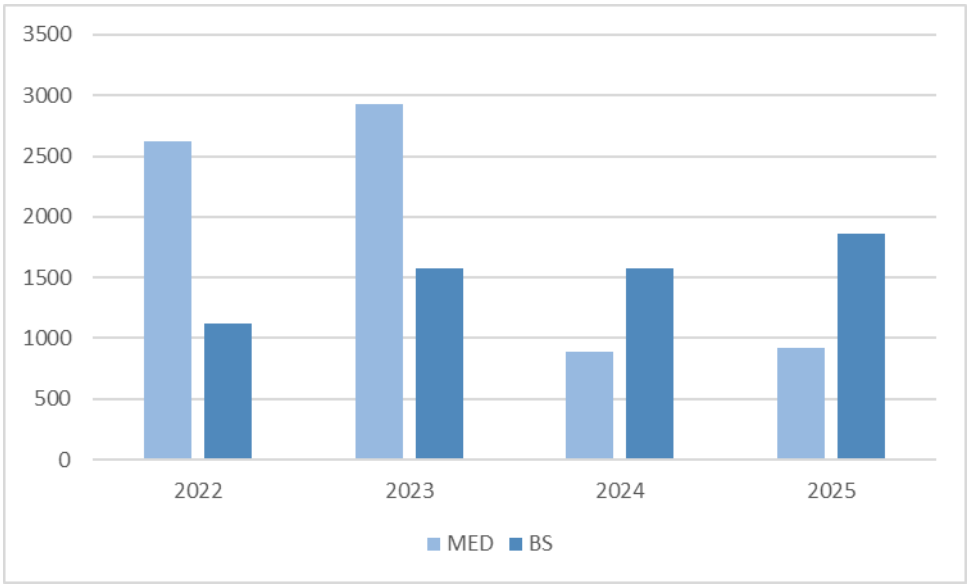


Figure 4. The inbound/outbound container traffic in the East Med and Black Sea areas yearly.

In 2023 we note an initial increase of container traffic of 2928 ships entering and exiting the Mediterranean Sea, 1571 ships for the Black Sea, compared to 2618 and 1122 ships during 2022 respectively. Immediately after that in 2024 we observe a drastic drop to 883 ships visiting the Mediterranean Sea, but surprisingly no significant change in the Black Sea with a total of 1580 ships. These numbers remain true during 2025 with a slight increase to 924 container vessels for the Mediterranean Sea and 1864 container vessels for the Black Sea. The numbers are consistent with the expected initial drop caused by a new crisis and the slow path to the recovery of the market.

The sharp drop is even more evident in Figure 5, showing traffic on a monthly basis. As a result, the transit times for shipments to Europe from the Far East increased by at least 10 days, increasing freight levels, carbon imprint, and causing a significant initial chaos in the supply chains. Here we observe a peak of 277 container ships visiting the Mediterranean Sea in August 2023, followed by a sharp drop to 80 vessels in January 2024, while at the same time noting a slight increase from 120 ships in January 2022 to 169 in November 2025.

Such situation put major East Mediterranean hub ports like Thessaloniki and Piraeus in a difficult situation. The data from UNCTAD (UNCTAD, 2024) and further published by www.ceicdata.com confirms there was a drop in container turnover of Greek ports, while Turkish saw an increase. However, the annual financial report of Piraeus shows they were managing the situation well. One could speculate that the reason is Greece's traditional export hub position for Macedonia and western Bulgaria (Greek ports are closer in road distance to Sofia and west Bulgaria region than Varna and Burgas). Nevertheless, the inbound ocean traffic was redirected to western med ports, such as Fos sur Mere, Genova and Gioia Tauro, giving them a far more significant role as transhipment hubs than the ones in Greece.

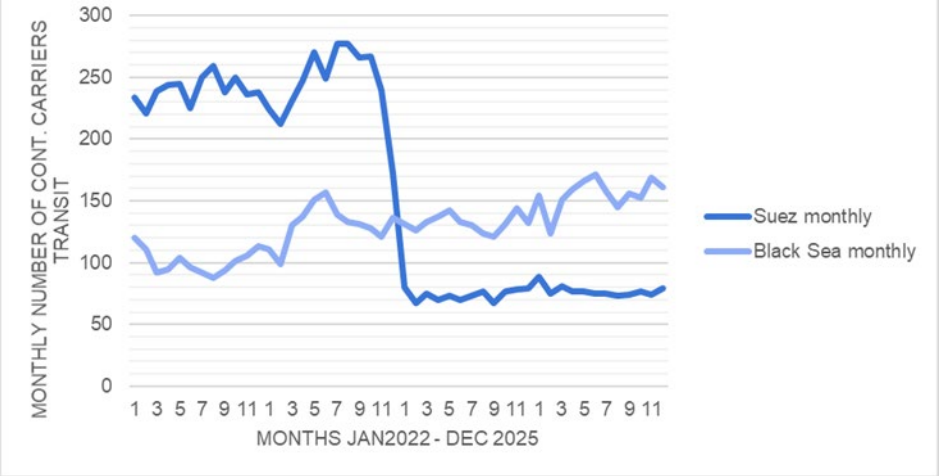


Figure 5. Suez and Bosporus monthly container carrier traffic.

Figure 6 demonstrates a comparison of container traffic of Turkiye and Greece for the period 2013-2024. It clearly indicates a drop in the container turnover in Greek ports, especially in the year 2023, while at the same time, there is an increase for Turkish ports. This further confirms the role of Turkish ports as a transhipment hub for Black Sea region.

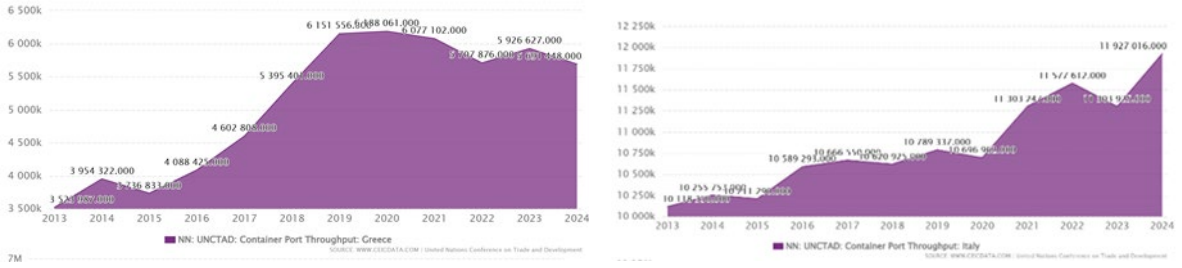


Figure 6. Comparison between turnover of containers in Greek (left) and Turkish (right) ports (source www.ceicdata.com).

There is one more significant feature that affects the East Med/ Black Sea trade, and it is the increase in cost for passing both the Suez Canal and the Bosporus. The cost for using the Suez Canal increased by 5 to 15% in 2023, following the drop in the number of vessels passing through it, as well as an increase in energy and maintenance costs. On the other hand, the increase in fees for passing the Bosporus and the Dardanelles in 2025 has had an even more significant effect on Black Sea maritime endeavours, including shipbuilding and repair, pilot services (the demand has decreased significantly due to diminished traffic), and tugboat services. recovery without a stable economic and political situation.

4. Conclusion

In summary of the above research, the following conclusions can be drawn:

- The political crisis in the Black Sea region, due to its long development, has had a deep impact on international trade and connections, resulting in a shrinking of the container market and a reduction in volumes,
- The post-COVID recovery did not happen as planned due to the Russia-Ukraine war. The high risk from drone attacks and maritime mines has made black Sea extremely unattractive for port calls, with increased war-like risk cover, high Bosporus/ Dardanelles transit tax, and infringed export volumes for local economies,
- The Gaza war, resulting in the Red Sea crisis, has had a significant impact on Suez transit and thus has disrupted most of container line services connecting Europe with the Far East and has shifted major hub ports from the Eastern Mediterranean area to the Central Mediterranean,
- These turbulent events have forced most ports in the East Mediterranean and Black Sea to adapt quickly to the changing geopolitical climate.

All the above-mentioned events, the resulting political and economic effects, as well as the high risk in shipping, have deeply affected the seaborne trade, not only in the Black Sea, but also in the entire region of the Eastern Mediterranean. This further confirms the sensitivity of shipping and container trade in particular to all economic and political turmoil. Even so, the East Mediterranean and Black Sea practitioners in container trade have demonstrated high flexibility and adaptability to a fast-changing environment. However, with ever-growing uncertainty and more and more crisis situations emerging worldwide, one cannot hope for a firm recovery without a stable economic and political situation.

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A Framework for Instructor Competency Criteria in Simulator-Based Maritime Training

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Abstract: Simulator-based training has become widely used in high-risk industries such as maritime and aviation. While advanced simulator systems support realistic training conditions, the effectiveness of training largely depends on the instructor. In many cases, instructor competency is described only in general terms, focusing on experience or certification, without clearly specifying the skills required during simulator-based exercises.

This study proposes a framework for instructor competency criteria in simulator-based training for maritime education and training (MET) institutions. The framework focuses on the combined role of technical and non-technical skills required during the simulator training. Technical skills include understanding simulator systems, scenario setup, system limitations, and the ability to monitor technical performance. Non-technical skills include communication, situational awareness, decision-making, leadership, and workload management. Rather than treating these skills separately, the framework explains how they are used together during the briefing, execution, and debriefing sessions. Attention is given to how instructors adjust the difficulty of scenarios, observe trainee behavior, respond to unexpected situations, and provide effective feedback after the exercise.

The framework also considers how instructors influence the transfer of learning from the simulator environment to real operational settings. By organising instructor competencies into a clear and practical structure, this study aims to support more consistent instructor development and evaluation. The proposed framework is aimed as a practical reference for MET institutions seeking to improve the quality and reliability of simulator-based training.

Keywords: Maritime simulator, instructor competency, simulator-based training, technical skills, non-technical skills.

1. Introduction

Simulator-based training is considered best practice to train as though the simulated scenarios are taking place in a real work environment, given that trainees are acting within simulated scenarios as if they were real situations (Dieckmann 2006), thereby practicing and gaining a deeper understanding of the complexities involved in professional tasks (Dieckmann et al. 2007; Rystedt and Sjöblom 2012). Nonetheless, literature has also highlighted that trainees may drift from professional framing through playful orientations, which underscores the importance of careful and structured pedagogical design in simulator-based training (Starup et al. 2024). Simulators therefore remain an essential tool for the education and training of seafarers, allowing seafarers to develop their skills in controlled and repeatable conditions while combining tasks and real-world contexts to facilitate knowledge transfer (Munim et al. 2025; Xue et al. 2024).

The instructor serves as the primary link between the simulator as a training tool and the trainee, facilitating the delivery of instruction (Rao 1990). Instructors play a crucial role not only in the success of the training program but also in facilitating effective learning through the briefing, executing scenario, and debriefing stages in simulator-based training programs (Lupu et al. 2014; Sellberg 2017; Christopoulos and Stylios 2024).

Despite this crucial role of the instructor, the qualification requirements of maritime simulator's instructors are defined in general terms. One of the four pillars of the International Maritime Organisation (IMO) is the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), which provides a regulatory framework for maritime training; however, it requires instructors to be appropriately qualified without providing detailed qualifications (STCW 2017). Existing training programs and industry standards address instructor qualifications at a general pedagogical level, but do not systematically explain demands placed on an instructor operating within a simulation environment. On the other hand, these training programs and industry standards were also developed at a time when simulator technology was premature comparing its current level; the integration of virtual reality / augmented reality (VR / AR), and artificial intelligence (AI) assisted tools into training environments makes the need for a technology-aware competency framework more pressing.

This paper addresses above mentioned gap by proposing a structured framework for instructor competency criteria in simulator-based maritime training. The framework organises the skills an instructor must hold and deploy into technical and non-technical domains, and maps these competencies to the distinct phases of a simulator training session. The aim is to provide MET institutions with a practical reference for instructor development and evaluation, and to contribute to more consistent standards across the sector.

2. Regulatory and Institutional Background

2.1 International Regulatory Framework

The main reference point for the qualifications of instructor in maritime training is Regulation I/6 of the STCW Convention, which requires that all instructors must be appropriately qualified in accordance with A-I/6 of the STCW Code. For simulation specifically, Section A-I/12 of the STCW Code draws out the standards applicable to the use of simulators in training and assessment, establishing minimum performance standards but not describing the qualifications of the simulator instructor (STCW 2017). With the goal of addressing this gap, IMO has introduced two instruments for instructor preparation. The first one is IMO Model Course 6.09 - Training Course for Instructors (IMO 2017) which establishes pedagogical foundation for MET with addressing learning objectives, teaching methods, and assessment design.

The second one is IMO Model Course 6.10 - Train the Simulator Trainer and Assessor (IMO 2012) which focused on simulator-based maritime training in the respect of the use of simulators for competence assessment and role-playing techniques with the objective of training the future assessors not only for training policy but also pedagogy skills along with providing them with a basis for evaluating the entire training process. Even tough this course considers seafaring background is a must for instructors, its scope remains broadly procedural and does not provide a competency framework for the technical and non-technical dimensions of the instructor's role in a simulator-based maritime training.

2.2 Classification Society and Industry Programmes

In addition to IMO framework, there are some available instructor training and certification programmes that classification societies and authorised organisations offer complementing international requirements. DNV provides a Train the Trainer for the Maritime Industry course aligned with IMO Model Course 6.09, targeting maritime trainers from various roles in the domain (DNV 2026a). Separately, DNV's SeaSkill™ learning programme certification (DNV-ST-0008) enables MET institutions to certify that their courses and instructor's qualifications comply with industry standards and relevant guidelines such as IMO Model Courses and DNV Competence Standards (DNV 2026b).

ClassNK provides the NK Training Course for Maritime Instructors programme which is designed as a practical digest of IMO Model Course 6.09 and addresses pedagogical fundamentals (ClassNK 2026). The other one is Virtual Marine, in partnership with the Nautical Institute, offers the Maritime Simulation Instructor and Assessor Training Program which addresses learning in a virtual environment, scenario creation, delivering simulation programmes, and simulation-based assessment, in accordance with IMO Model Course 6.09 and IMO Model Course 6.10 (Virtual Marine 2025).

Table 1 depicts a comparative overview of the available standards and programmes relevant to simulator instructor preparation.

Table 1. Overview of available standards and programmes for simulator instructor preparation.

Organisation / Source	Programme / Standard	Scope and Relevance to Simulator Instruction
IMO	STCW Regulation I/6; Section A-I/6 & A-I/12	Requires instructors to be appropriately qualified; sets simulator performance standards
IMO	Model Course 6.09	General pedagogical training; learning objectives, teaching methods, assessment design
IMO	Model Course 6.10	Simulator - specific; scenario delivery, role-playing, STCW compliance
DNV	Train the Trainer	IMO 6.09 aligned; maritime instructor preparation; teaching aids, training design
DNV	SeaSkill™ (DNV-ST-0008)	Certification of learning programmes; verifies course quality and instructor competence
ClassNK	NK Training Course for Maritime Instructors	Pedagogical fundamentals; IMO 6.09 digest; on-site delivery
Virtual Marine / Nautical Institute	Maritime Simulation Instructor and Assessor Training Program	STCW A-I/6 and A-I/12, IMO 6.09 and IMO 6.10 aligned; scenario creation, simulation delivery, assessment

2.3 Identified Gap

Even though IMO framework and complementary training programmes indicate the importance of simulator instructor, their limitation is common: their approach to instructor preparation is primarily through a pedagogical perspective, without providing an integrated framework that differentiates what a simulator instructor must know and do, in terms of both technical and non-technical competence across each phase of a simulator-based maritime training. Furthermore, none of the existing programmes systematically focus on how instructor competency must adapt as simulator technology itself evolves. This gap becomes increasingly significant as VR, AI-assisted analytics, and advanced navigation systems reshape the training environment. This paper aims to address the gaps identified above.

3. Technical and Non-Technical Competencies of the Simulator Instructor

The primary focus of the proposed framework is that the competencies in question belong to the instructor, not the trainee. This distinction is pivotal: the existing literature on technical and non-technical skills in maritime training largely focus on the competencies that seafarers are expected to acquire and sustain. Conversely, this paper describes the skills that an instructor must independently have to design, manage, and evaluate the training experience effectively.

3.1 Technical Competencies

The technical competencies of a simulator instructor are not entirely reflected in the extent of operational experience at sea. Published literature emphasises that the sole experience does not yield maximal performance; rather, practice and its quality are the indicators of the competency improvement (Ericsson et al. 1993). Similarly, a long-serving seafarer who operated in routine voyages may have encountered fewer professional challenges than the one with shorter but more demanding operational career. Therefore, years of seagoing experience cannot serve as a meaningful measure of pedagogical preparedness of the instructor. Firstly, the instructor must have a comprehensive understanding of the simulator system being used including its architecture, capabilities, and interface to the extent that they can configure and operate it during a training

session. This includes the ability to adapt training scenarios, meeting trainee's needs and abilities, adjusting parameters based on course objectives, and even taking on various roles to enhance scenario fidelity (Longo et al. 2015; Sanfilippo 2017).

Secondly, the technical limitations of the simulator must be understood by the instructor. Regardless of fidelity level simulator has, every systems have limitations relative to real-world conditions. An instructor must create a link between system limitations and real-world conditions (IMO 2012; Brčić et al. 2025). If these limitations cannot be recognised by instructor, incorrect procedural habits may arise. This becomes particularly relevant in the context of integrated navigation system simulators, where distinguishing between software model behaviour and genuine trainee error is far from straightforward and virtually impossible without an adequate understanding of the system itself.

A third dimension of technical competency concerns the instructor's ability to monitor trainee performance through the simulator's built-in observation and data-logging tools. Being able to interpret the system's output such as identifying deviations, recognising decision points, and reading performance trends, is equally important, as it directly shapes the quality of feedback delivered during debriefing (Marcano et al. 2019). This is different from simply watching what is happening on screen. It requires the instructor to actively draw on the simulator's technical features as a source of evidence-based support for meaningful, targeted feedback.

3.2 Non-Technical Competencies

The non-technical competencies of a simulator instructor are largely pedagogical and interpersonal in nature. Together, they enable the instructor to build and sustain a productive learning environment across all phases of simulator-based training while continuously monitoring trainees' comprehension and providing meaningful guidance throughout (Nazir et al. 2018). Importantly, the depth of these competencies has a direct bearing on how effectively the simulator is used as a pedagogical tool and, by extension, on the overall quality of training outcomes (Kim et al. 2021; Tsoukalas et al. 2008).

Among non-technical competencies, communication skills occupy a central position (Sidelinger et al. 2015). During the briefing phase, the instructor must be able to thoroughly orient trainees to the session by articulating the learning objectives, outlining the scenario parameters, and setting clear expectations for behaviour. During debriefing, it is once again communication that determines whether feedback lands constructively and whether the learning experience is meaningfully consolidated.

Situational awareness stands out as another indispensable competency. In this context, it refers to the instructor's ability to simultaneously track the progression of the exercise, the behaviour of individual trainees, the operational state of the simulator, and the broader trajectory of the learning session (Lazure et al. 2020). This is a cognitively demanding balancing act requiring the instructor to maintain a coherent overall picture without becoming overly absorbed in any single aspect of the unfolding scenario.

Decision-making is equally consequential, especially when it comes to the question of whether and how to intervene during a live exercise (Brčić et al. 2025). The instructor must judge, in real time, whether a trainee's difficulty represents a learning opportunity worth preserving or a situation that calls for redirection before errors begin to compound. Finally, workload management and leadership are both highly relevant competencies, as the instructor ultimately serves as the orchestrator of the simulation environment, simultaneously balancing the demands of system operation, active observation, and facilitation.

4. The Proposed Framework

4.1 Design Principles

The framework is built on two core design principles. The first holds that instructor competencies are not isolated traits. They are deployed in combination and must be understood in relation to the specific phase of the training session in which they are most actively engaged (Brčić et al. 2025). The second establishes that technical and non-technical competencies are fundamentally interdependent, and neither can be fully effective in the absence of the other. An instructor who is technically proficient yet unable to communicate observations clearly will inevitably fall short during debriefing. Conversely, an instructor with strong

communicative abilities but an insufficient understanding of the simulator may misread performance data or struggle to construct scenarios of appropriate fidelity.

4.2 Framework Structure: Instructor Competency Across Training Phases

The framework organises instructor competencies across three phases: pre-session preparation and briefing, session execution, and debriefing. For each phase, the specific expression of technical and non-technical competency is described from the instructor's perspective. Table 2 presents this phase-structured framework.

Table 2. Instructor competency framework designed for simulator training phases.

Training Phase	Instructor's Technical Competency	Instructor's Non-Technical Competency
Pre-Session / Briefing	Scenario design aligned with learning objectives; simulator configuration; calibration of difficulty; knowledge of system limitations relevant to the scenario	Clear communication of objectives; structured briefing delivery; establishing a pedagogical safety climate for learning
Execution	Real-time system monitoring; use of instructor operator station; recognition of simulator artefacts versus trainee errors; dynamic scenario adjustment	Sustained situational awareness of trainee performance; decision to intervene or observe; workload management across concurrent monitoring tasks
Debriefing	Evidence-based review using simulator data and playback tools; interpretation of performance indicators	Structured feedback delivery; constructive communication; leadership in facilitating reflection; linking observed performance to learning objectives

To address the preliminary validation need of the proposed framework, expert consultations were conducted with three experts from two institutions who hold IMO Model Course 6.10 certification and are actively serving as an instructor in simulator-based training. Experts were requested to assess the comprehensiveness and relevance of the instructor competency criteria shown in Table 2 and their applicability in MET institutions. The expert consultations yielded a consensus confirming the appropriateness of the proposed framework, with no structural revision suggested.

4.3 Adaptive Dimension: Responding to the Unexpected

A further element of the framework is the instructor's adaptive competency which refers to the capacity to respond effectively to unexpected events while they arise during the exercise. Such events may include technical failures, trainees who perform significantly above or below the intended difficulty level, or emergent behaviours that the scenario was not originally designed. In such moments, the instructor must draw simultaneously on technical competency such as diagnosing and managing the state of the system, and non-technical competency such as determining how to reframe the situation pedagogically and conveying that reframing clearly to trainees. Crucially, this adaptive dimension should not be treated as a distinct skill set in its own right; it is, rather, the integrated expression of all the competencies outlined above, brought to bear under conditions of uncertainty.

4.4 Learning Transfer: The Instructor's Role

The ultimate purpose of simulator-based training is not performance within the simulation itself, but the transfer of competencies to real operational settings. The instructor plays a determinative role in this process. The quality of the debriefing - more specifically, the instructor's ability to connect observed behaviour in the simulation to the principles and standards that govern actual operations - constitutes a primary mechanism through which simulator training acquires its practical value. An instructor who debriefs solely at the level of error identification, without grounding observations in the underlying competencies, operational norms, or regulatory expectations at stake, will substantially limit the transfer potential of the exercise regardless of how well the simulation itself was technically executed.

4.5 Adaptation to Emerging Technologies

The competency framework proposed in this paper should be understood as dynamic rather than static. Simulator technology in the maritime domain is evolving rapidly, and the instructor's technical competency must keep pace with the systems being used in training. This evolution places specific adaptive demands on the instructor across several interconnected dimensions.

The growing integration of VR and AR platforms into maritime simulation introduces a particularly significant layer of adaptive demand. These systems support the simulation of hazardous operations in a safe environment while enhancing learning outcomes and trainee engagement in contrast to conventional simulation methods (Christopoulos and Stylios 2024). Moreover, they offer substantially higher levels of sensory immersion than conventional screen-based simulators, and this shift requires more than simple familiarity with new hardware and software interfaces. Therefore, instructors must invest substantial time and effort not only for developing sufficient operational familiarity but also for facilitating learning within integrated technologies (Kim et al. 2021). This calls for an updated understanding of how immersive environments affect trainee cognition, stress responses, and learning transfer. The instructor's non-technical competencies such as situational awareness and feedback delivery in particular, must be recalibrated accordingly, given that the trainee's perceptual experience in these environments differs considerably from that of conventional simulation settings.

The integration of AI tools into maritime training platforms in the form of automated performance analytics, adaptive scenario generation, and AI-assisted debriefing support, presents both considerable opportunity and a substantive professional concern. While these developments have the potential to enhance the quality and consistency of instruction, they require instructors to develop a critical understanding of what AI-generated performance data can and cannot reveal. Uncritical reliance on automated analysis risks eroding the observational and interpretive competency that constitutes the foundation of effective facilitation. In an AI-augmented training environment, the instructor's role is therefore not diminished but reoriented: from primary observer to critical interpreter of machine-generated evidence.

Taken together, these developments indicate that the framework proposed in this paper should be accompanied by a continuous professional development requirement for simulator instructors. Competency in operating and interpreting a simulator cannot be achieved once and assumed to remain valid as the underlying technology evolves. MET institutions should therefore treat instructor technology adaptation not as an optional enhancement but as a core element of the competency maintenance obligations implied by STCW Regulation I/6.

5. Discussion

The framework proposed in this paper departs from existing standards and training programmes in a meaningful respect. International legal framework such as STCW Regulation I/6 and IMO Model Courses 6.09 and 6.10 establish that instructors must be qualified and offer broad guidance on pedagogical preparation. Industry programmes from classification societies and organisations such as DNV, ClassNK, and Virtual Marine translate these requirements into concrete training curricula. Yet what has consistently been missing is a structured framework that links instructor competency to the specific operational settings of a simulator session one that addresses not only which competencies matter, but when and how they actually come into play.

The framework proposed here is intended to complement existing standards, not to replace them. MET institutions may find it a useful reference when designing instructor development programmes, constructing evaluation rubrics, or reflecting on how well their current simulator training practices align with the competency expectations they already place on instructors. The phase-structured approach seems especially relevant for training institutions that carry out post-session evaluations, since it offers a principled way to distinguish between what an instructor handles well or less well at each stage of an exercise. The technology adaptation dimension explored in Section 4.5 further suggests that this should be treated as a living process rather than a one-time review.

6. Conclusion

This paper has proposed a framework for instructor competency in simulator-based maritime training, structured around the integration of technical and non-technical skills across three phases of a training session. The framework makes explicit that the competencies required of a simulator instructor are distinct from, even if related to, the competencies being developed in trainees, and that technical proficiency and pedagogical skill must work in combination if training is to achieve its intended outcomes.

By organising these competencies in a phase-structured and practically grounded format, the framework aims to support MET institutions in developing more consistent and rigorous approaches to instructor preparation and evaluation. As simulator technology continues to advance and the demands placed on maritime training grow increasingly complex, the competency of the instructor will remain one of the most consequential factors shaping training outcomes. Investing in sophisticated simulation environments is not sufficient if the instructors operating within them lack the preparation to use those environments well.

A limitation of the present work is that the framework has been developed through a synthesis of regulatory documents, industry standards, and published literature, and has been subject to preliminary expert consultation rather than large-scale empirical verification. Future research should seek broader validation through structured surveys with a large population of experienced simulator instructors and MET institution managers. It would also be valuable to examine how the framework might be adapted to specific simulator types, distinct operational contexts and scenarios, and the emerging generation of training technologies including VR and AR environments and AI-assisted performance analysis tools that are beginning to reshape what simulator-based maritime education can achieve.

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Smart and Sustainable Marinas: Digital Transformation, Digital Competencies and Organizational Performance

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Abstract: The marina and recreational boating sector is undergoing digital transformation in response to evolving customer expectations, increased competition, environmental challenges, and technological advancements. Digital solutions increasingly support integrated and sustainable marina operations through real-time berth tracking, automated contract management, predictive maintenance, analytics, and environmental monitoring. However, limited research examines how digital transformation across marina operational domains influences multidimensional marina performance outcomes, including financial, customer, internal process, safety, innovation, growth, and environmental dimensions. This study proposes a framework connecting digital solutions, digital competencies, training and education, marina performance outcomes, and the main enablers and constraints of digital transformation. The research employs a qualitative approach based on secondary qualitative analysis and in-depth interviews with marina professionals from operations, management, engineering, digital systems and IT support, administration, safety, marketing, and environmental management. Findings indicate that digital transformation significantly influences marina performance outcomes, while its effectiveness increasingly depends on digital competencies, continuous training and education, organizational readiness, and sustainability-oriented operational practices. The proposed framework contributes to smart marina and sustainable nautical tourism literature by integrating digital solutions and transformation, competencies, and multidimensional marina performance outcomes within a single conceptual structure. The findings provide practical implications for marina managers, policymakers, educators, and training providers.

Keywords: marina management; digital solutions; digital competencies; business performance; sustainable nautical tourism

1. Introduction

Digital technologies and innovations are increasingly reshaping business operations, organizational processes, and service delivery across industries, accelerating digital transformation (DT) and changing the way organizations create value and respond to evolving market and environmental challenges. The marina and recreational boating sector is undergoing a significant transformation as operators respond to increasing customer expectations, growing competition, sustainability pressures, and rapid technological development (ICOMIA, 2023; Innovamarina, 2023). Marinas are complex nautical infrastructures that integrate diverse facilities, services, and operational functions related to recreational boating, vessel berthing, maintenance, tourism, and customer support activities (ICOMIA, 2023; Mundula et al., 2020). As an important segment of the recreational boating and nautical tourism industry, marinas operate within dynamic environments characterized by increasing customer expectations, environmental pressures, technological advancements, and sustainability requirements (Tonazzini et al., 2019; Martínez-Vázquez et al., 2021). Consequently, marina management increasingly requires the integration of digital technologies and smart solutions to improve operational efficiency, service quality, environmental management, safety, and long-term competitiveness (Maglić et al., 2021; Radulovic, 2022; Mohammed et al., 2024).

Digital transformation (DT) in the marina industry involves integrating digital technologies, smart systems, and data-driven solutions across diverse operational domains and managerial processes. Contemporary marinas

increasingly implement technologies such as integrated management platforms, Internet of Things (IoT) systems, artificial intelligence (AI), smart monitoring systems, mobile applications, cloud-based platforms, and real-time communication technologies to improve operational coordination, customer experience, safety, environmental monitoring, and resource efficiency (Mundula et al., 2020; ICOMIA, 2023; Manojlović et al., 2024; Lee et al., 2025). In this context, digital solutions are not limited to technological modernization; they increasingly serve as strategic tools for improving operational performance, decision-making, sustainability management, and long-term competitiveness in the nautical tourism sector (Radulovic, 2022; Ioras and Bandara, 2025). Leading international marina groups (e.g., ACI Marinas, n.d.; D-Marin, n.d.; IGY Marinas, n.d.; Premier Marinas, n.d.) increasingly integrate smart infrastructure, digital customer platforms, sustainability-oriented technologies, and data-driven management systems into marina operations to improve multidimensional marina performance outcomes.

In parallel with technological transformation, marinas are increasingly exposed to sustainability pressures related to environmental protection, resource management, energy efficiency, regulatory requirements, and the long-term resilience of coastal and marine tourism systems (Tonazzini et al., 2019; CPMR and MedWaves, 2022). Digital technologies and smart solutions can support more sustainable marina management through real-time monitoring, predictive maintenance, optimized resource consumption, environmental control systems, and improved operational transparency (Innovamarina, 2023; ICOMIA, 2023). However, the implementation of DT strategies in marinas is often constrained by financial limitations, organizational resistance, infrastructure complexity, cybersecurity concerns, and insufficient digital competencies among personnel and management (Brunetti et al., 2022; EBI, 2023; Ng et al., 2023; Avelar et al., 2024). Furthermore, DT radically changes the modus operandi of human work and communication, requiring the ongoing development of digital competencies (Praničević et al., 2023). Consequently, successful marina DT depends not only on integrating digital technologies and smart solutions but also on managerial support, personnel training, digital competencies, and the ability to adapt operational and organizational practices to evolving technological and sustainability requirements.

Despite the growing relevance of DT and smart marina development, existing research dominantly focuses on digital solutions, smart marina applications, sustainability practices, or operational digitalization separately (e.g., Tonazzini et al., 2019; Mundula et al., 2020; Maglić et al., 2021; Martínez-Vázquez et al., 2021; Radulovic, 2022; ICOMIA, 2023; Innovamarina, 2023; Manojlović et al., 2024; Mohammed et al., 2024; Ioras and Bandara, 2025), while limited attention has been given to the integrated relationships between DT, human capital, and marina performance outcomes (Lee et al., 2025). In particular, there is limited research addressing how DT of marina operations interacts with digital competencies, personnel training, and performance outcomes, including financial, operational, customer, innovation, safety, and environmental outcomes. To address this gap, this study investigates the impact of DT across marina operational domains on marina performance outcomes. The paper analyses how digital solutions are implemented within core marina operational areas, including nautical operations, customer services, sales and marketing, technical and infrastructure management, and administrative and managerial activities. Using a qualitative research approach grounded in academic literature, industry reports, professional publications, and expert interviews, the study examines the relationships among DT solutions, human capital and digital competencies, and multidimensional marina performance dimensions. Based on these relationships, the paper proposes an integrated conceptual framework for analysing sustainable and strategically oriented marina DT.

2. Materials and Methods

The purpose of this study is to investigate how digital transformation across marina operational domains influences marina performance outcomes, considering the role of digital competencies, training and education, and key enablers and constraints of digital transformation. The research model (Figure 1) consists of five stages.

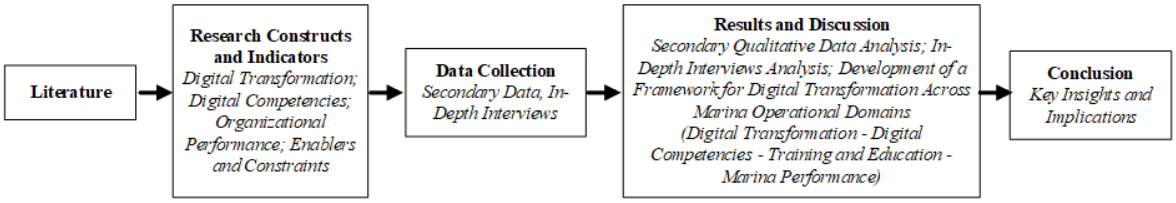


Figure 1. Research model.

The empirical research employs a qualitative approach and interview-based insights derived from both secondary and primary data sources. Secondary data were collected through document-based analysis of published industry interviews in professional marina publications (e.g., Marina World, n.d.; EBI, 2023), materials from leading international marina groups, and other industry sources. Primary qualitative data were collected through semi-structured in-depth interviews with eight (8) industry experts in marina operations, management, engineering, digital systems and IT support, administration, marketing, safety, and environmental management. Interviews were conducted online and in person between March and April 2026 using a semi-structured questionnaire, with an average duration of 40 to 60 minutes. The interview protocol was structured around the research constructs presented in Table 1, allowing respondents to discuss the implementation of digital solutions, digital competencies, training practices, performance outcomes, and key enablers and constraints of marina digital transformation. Qualitative data obtained from primary and secondary sources were analysed using thematic and interpretative analysis to identify recurring patterns, operational practices, and relationships among digital transformation, competencies, and marina performance dimensions. Based on the findings, the study proposes a conceptual framework for marina digital transformation, digital competencies, and performance outcomes.

Table 1: Research constructs and interview-oriented main questions.

Digital transformation of marinas, performance outcomes, human capital, enablers, and constraints
Which digital technologies and solutions are applied in the global marina industry?
Which digital solutions are integrated across the operational domains of marinas?
How well is digital transformation aligned across different operational domains of marinas?
How do industry experts perceive the current level of digital transformation in the marina industry?
How do DT solutions across marina operational domains impact multidimensional performance outcomes?
Which competencies are required for the digital transformation of marinas? Which competencies are lacking?
What is the level of digital competencies in the marina industry?
What is the role of digital training and education in the digital transformation of marinas?
What is the level of investment in digital competencies, training, and education within marinas?
How do marinas evaluate the outcomes of digital training and education initiatives?
What are the main internal and external enablers and constraints for the digital transformation of marinas?

The main research questions of this study focus on how DT across marina operational domains influences marina performance outcomes, how digital competencies, training, and education support DT, and which enablers and constraints influence its implementation. Based on the research aims and literature analysis, the study developed four interrelated research constructs: i) DT across marina operational domains, ii) digital competencies, training and education, iii) marina performance outcomes, and iv) enablers and constraints of DT. Table 1 presents the main interview-oriented research questions.

Marina operational domains analysed in this study include: i) core marina operations (primary nautical operations), ii) infrastructure and technical systems, iii) sales and marketing, and iv) management and administrative systems. Digital transformation was examined through the implementation of technologies and smart solutions, including IoT, AI, 5G, digital twins, cybersecurity systems, blockchain, big data, and related digital applications. Performance outcomes of marina were interpreted through financial, customer, internal processes, innovation and growth, safety, and environmental dimensions. Digital competencies were interpreted using the DigComp framework (Cosgrove and Cachia, 2025), which includes competencies related to information management, communication and collaboration, content creation, safety and responsible use, and

problem-solving. Indicators related to training and education included participation in DT training, investments in employee education, and post-training evaluation practices (World Tourism Organization, 2023). Indicators for enablers and constraints included DT strategy, implementation risks, financial resources, funding, organizational culture, external policies and institutional support, regulations and law, and workforce availability.

3. Results and Discussion

3.1. Results from the Qualitative Analysis of Secondary Data

Table 2. Results of the qualitative analysis of secondary data.

Theme	Secondary qualitative industry evidence	Implications for marina performance and framework development
DT and operational performance	The increasing adoption of integrated marina management platforms, AI-supported analytics, smart monitoring systems, digital contracting, and real-time operational control technologies supports coordination, berth management, customer interactions, and administrative efficiency.	DT increasingly supports operational efficiency, customer experience, data-driven decision-making, financial performance, and competitiveness across marina operational domains.
Digital competencies, training, and organizational adaptation	Successful implementation of DT solutions increasingly depends on personnel's digital competencies, continuous staff training, operational readiness, and marina organizations' ability to adapt to evolving digital systems and service requirements.	Digital competencies, training practices, and organizational adaptation are increasingly critical to the effective implementation of DT strategies and the sustainable transformation of marina operations.
Sustainability-oriented digital transformation	Growing implementation of smart metering systems, environmental monitoring technologies, digital twins, predictive maintenance systems, and data-driven sustainability solutions supports energy efficiency, water management, safety, and environmental protection in marina operations.	DT increasingly contributes to sustainability-oriented marina management by improving environmental monitoring, resource optimization, operational monitoring, and the long-term resilience of marina infrastructure and coastal tourism systems.
Enablers and constraints of marina DT	Financial investments, infrastructure readiness, digital competencies, organizational adaptation, and institutional support represent important enablers of marina digital transformation, while cybersecurity concerns, implementation costs, organizational resistance, and operational complexity remain significant constraints.	The successful implementation of marina DT increasingly depends on integrating technology-related, organizational, managerial, and competency-related factors across diverse marina operational domains.

Published marina industry interviews, strategic reports, and expert discussions (Marina World, n.d.; ICOMIA, 2023; EBI, 2023) indicate that DT increasingly influences operational efficiency, customer experience, sustainability practices, and managerial processes across the global marina industry. Results from the qualitative analysis of the secondary data (Table 2) indicate that DT in the marina industry increasingly extends beyond technological modernization toward integrated operational, organizational, and sustainability-oriented transformation processes. The findings confirm that digital solutions are progressively embedded across diverse marina operational domains, influencing operational efficiency, customer experience, environmental management, and competitiveness. Consistent with broader DT literature, the successful implementation of digital technologies increasingly depends not only on the implementation of digital solutions but also on human capital, digital competencies, training, education, and organizational adaptation (Brunetti et al., 2022; Praničević et al., 2022; Giraud et al., 2023; Ng et al., 2023). Furthermore, the findings support the growing importance of multidimensional performance perspectives for evaluating marina DT outcomes across financial, customer, internal processes, innovation, safety, and environmental dimensions (Kaplan and Norton, 1996; Madsen, 2025). Sustainability-oriented digital transformation increasingly reflects broader industry pressures related to environmental responsibility, resource optimization, and long-term resilience of coastal tourism (CPMR and MedWaves, 2022; Plan Bleu, 2022).

3.2. Results from the qualitative analysis of interview-based primary data

Table 3 summarizes the main relationships identified through the qualitative analysis of interview-based primary data, including digital solutions, marina operational domains, required digital competency levels, training and education intensity, and marina performance outcomes. In Table 3, marina operational domains (MOD1-MOD4) and marina performance outcomes (MPO1-MPO6) are ordered according to the perceived intensity and directness of impact identified through qualitative analysis, ranging from dominant operational and performance effects toward indirect impacts across marina operational domains. Digital competency levels (basic, intermediate, advanced, highly advanced) were interpreted according to the DigComp 3.0 framework (Cosgrove and Cachia, 2025). Training and education intensity levels (low, medium, high) reflect estimated organizational effort, resource allocation, and continuous learning requirements associated with implementing and operating specific digital solutions and were interpreted based on competency development and training-related perspectives discussed by Ng et al. (2023) and World Tourism Organisation (2023).

Table 3: Digital solutions and marina performance outcomes

Digital solution	Marina Operational Domains (MOD)	Required Digital Competencies Level	Training, Education and Investments Level	Marina Performance Outcomes (MPO)
Integrated Marina Management Platforms	Examples: Berth management systems, digital booking/check-in, CRM/ERP integration, marina management software, real-time occupancy monitoring			
	MOD1, MOD4, MOD3, MOD2	Intermediate, Advanced	Medium, High	MPO3, MPO2, MPO1, MPO4, MPO5, MPO6
IoT and Smart Monitoring Systems	Examples: Smart sensors, vessel condition monitoring, smart pedestals, water/energy monitoring, smoke/bilge/battery alerts			
	MOD2, MOD1, MOD4, MOD3	Advanced, Highly Advanced	High	MPO5, MPO6, MPO3, MPO4, MPO2, MPO1
Customer Digital Platforms and Mobile Applications	Examples: Mobile applications, online reservations, digital customer communication, online payments, digital stay management			
	MOD3, MOD1, MOD4, MOD2	Basic, Intermediate	Low, Medium	MPO2, MPO1, MPO4, MPO3, MPO5, MPO6
Data Analytics and Decision-Support Systems	Examples: Real-time analytics, dynamic pricing, occupancy forecasting, business intelligence, predictive analytics			
	MOD4, MOD1, MOD3, MOD2	Advanced, Highly Advanced	High	MPO1, MPO3, MPO4, MPO2, MPO5, MPO6
Smart Infrastructure and Energy Management Systems	Examples: Smart electrical systems, energy optimization, water management systems, smart grids, environmental monitoring			
	MOD2, MOD4, MOD3, MOD1	Intermediate, Advanced	Medium, High	MPO6, MPO1, MPO5, MPO3, MPO2, MPO4
Workforce Digital Coordination Systems	Examples: Staff mobile applications, digital task management, incident-response systems, field-worker coordination platforms			
	MOD1, MOD4, MOD2, MOD3	Intermediate	Medium	MPO3, MPO5, MPO2, MPO4, MPO1, MPO6

Legends: MOD: MOD1 = Core Marina Operations; MOD2 = Infrastructure and Technical Systems; MOD3 = Sales and Marketing; MOD4 = Management and Administrative Systems; MPO: Financial (MPO1), Customer (MPO2), Internal Processes (MPO3), Innovation and Growth (MPO4), Safety (MPO5), and Environmental (MPO6).

The findings indicate that digital solutions across marina operational domains require varying levels of digital competencies, organizational adaptation, training and education, and investment requirements depending on the complexity and operational role of specific digital systems. In particular, advanced systems such as IoT monitoring technologies, analytics platforms, smart infrastructure systems, and AI-supported decision tools require higher levels of digital competencies and operational readiness, supporting broader discussions on the growing importance of digital literacy, AI-related competencies, and continuous learning processes within digitally transforming organizations (e.g., Brunetti et al., 2022; Giraud et al., 2023; Ng et al., 2023; Avelar et al., 2024; Cosgrove and Cachia, 2025). The findings also confirm that marina DT increasingly influences multidimensional performance outcomes. The analysis indicates that different categories of digital solutions influence marina performance outcomes with varying levels of intensity across marina operational domains. In particular, integrated management platforms and analytics systems were more strongly associated with internal

process efficiency, financial performance, and customer service improvements, whereas smart monitoring technologies and sustainability-oriented infrastructure systems were primarily associated with safety, environmental performance, and operational resilience.

The findings align with multidimensional performance perspectives discussed in strategic management and balanced scorecard literature, emphasizing the interconnected nature of financial, operational, customer, innovation, safety, and environmental performance dimensions within digitally transforming organizations (Kaplan and Norton, 1996; Hegazy et al., 2022; Manojlović et al., 2024; Madsen, 2025). Furthermore, the increasing integration of sustainability-oriented digital systems reflects broader industry pressures related to environmental responsibility, operational resilience, and the creation of long-term organizational and social value within coastal and marine tourism systems (Porter and Kramer, 2011; Tonazzini et al., 2019; CPMR and MedWaves, 2022; Bitencourt et al., 2024; Marušić et al., 2024, 2025). The findings support the development of a framework that integrates DT, competencies, training and education, and multidimensional marina performance outcomes.

The combined findings from the qualitative analysis of secondary data (Table 2) and interview-based primary data (Table 3) indicate that marina DT increasingly represents an integrated operational, organizational, and sustainability-oriented process involving interconnected digital solutions, digital competencies, training and education, and multidimensional performance outcomes. Both analyses highlight the importance of digital competencies, organizational adaptation, and sustainability-oriented operational practices in supporting marina transformation across operational domains, consistent with broader discussions on DT and multidimensional organizational performance (e.g., Kaplan and Norton, 1996; Tonazzini et al., 2019; Manojlović et al., 2024; Cosgrove and Cachia, 2025).

3.3. Framework for Marina Digital Transformation, Digital Competencies, and Performance Outcomes

Based on the combined findings from the qualitative analysis of secondary (Table 2) and primary data (Table 3), this paper proposes a framework for marina DT across operational domains, considering performance outcomes and with particular focus on digital competencies (Figure 2).

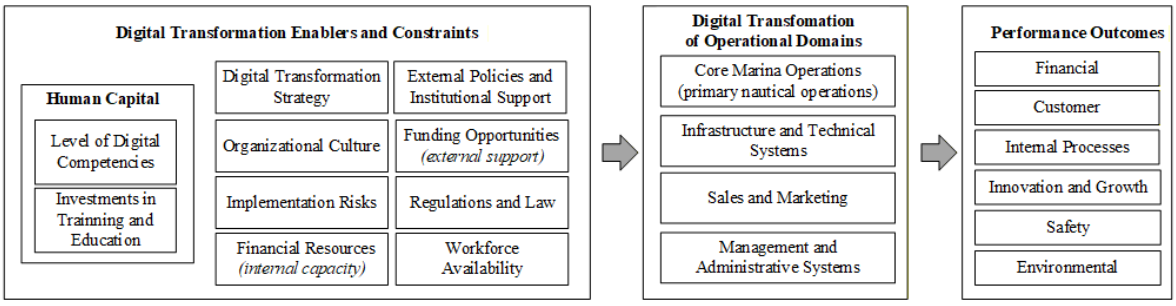


Figure 2. Framework for Marina Digital Transformation, Digital Competencies, and Performance Outcomes.

Figure 2 presents the conceptual framework for marina DT developed through the integration of academic literature, secondary qualitative evidence, and interview-based primary data. The framework links DT enablers and constraints, marina operational domains, digital competencies, training and education, and multidimensional performance outcomes within an interconnected transformation process. Unlike many existing smart marina and DT studies that primarily focus on technological applications or operational digitalization, the proposed framework integrates organizational, competency-related, and performance-oriented dimensions of marina DT across diverse operational domains (Mundula et al., 2020; Radulovic, 2022; Manojlović et al., 2024; Lee et al., 2025). The framework also incorporates transformation related to environmental responsibility, resource efficiency, safety, and operational resilience within coastal and marine tourism systems, consistent with broader discussions in DT and sustainable tourism literature (Brunetti et al., 2022; Giraud et al., 2023; Ng et al., 2023; Tonazzini et al., 2019; CPMR and MedWaves, 2022; Cosgrove and Cachia, 2025).

3. Conclusion and Limitations

This paper examined the role of digital transformation across marina operational domains, emphasizing the relationships among digital solutions, digital competencies, and multidimensional marina performance. The findings indicate that DT in marinas increasingly represents an integrated organizational, operational, strategic, and sustainability-oriented process involving interconnected digital solutions, digital competencies, operational practices, and performance dimensions. This study shows that DT across marina operational domains increasingly influences multidimensional organizational performance outcomes, and that the effectiveness of implementing digital solutions and the transformation process depends on digital competencies and continuous training and education. The proposed framework contributes to smart marina and sustainable nautical tourism literature by integrating digital solutions, marina operational domains, digital competencies, training and education, and multidimensional performance outcomes within a single conceptual structure. It may serve as an analytical tool for organizational transformation processes in sustainability-oriented maritime contexts.

Although the findings and the proposed framework provide new perspectives on contemporary research and practice and a novel conceptual basis for future empirical research and management practices, this study has several limitations. First, the study is based solely on qualitative analysis, on a limited number of secondary data sources, and on a limited number of in-depth interviews with experts, which restricts the generalizability of the findings. Furthermore, research constructs and indicators are narrowly operationalized, with a limited number of examples covered in the analysis. Additionally, the proposed framework is not empirically tested through large-scale quantitative or comparative marina studies. Therefore, future research should validate the framework through qualitative and quantitative empirical research, and further operationalize the constructs and indicators to deepen understanding of DT practices in marinas. This study contributes to a broader understanding of how DT, competencies, and organizational adaptation increasingly shape sustainable, performance-oriented transformation processes in maritime and blue economy contexts.

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Safety-Oriented Approach to Shipping Development Based on Quality Management of Technical Operation of a Vessel

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Abstract: Maritime transport is one of the fundamental sectors of the global economy and plays a significant role in ensuring the economic and national security of states. Economic security is closely linked to maritime safety, which encompasses the protection of human life, the marine environment and property from unacceptable operational risks. The effective functioning of a multi-level shipping safety system depends largely on the technical condition of vessels and the reliability of shipboard equipment and systems.

The purpose of this study is to examine a safety-oriented approach to shipping development through quality management of vessel technical operations. The research is based on a structured review of scientific publications, international maritime conventions and national regulatory documents published between 2015 and 2025. Eight key sources were analysed to identify the relationships between shipping safety, economic security and quality management practices.

The study clarifies the concepts of safety orientation, multi-level safety systems and quality management in ship technical operations. Based on the synthesis of the reviewed literature and regulatory requirements, a conceptual model is proposed that integrates safety principles with quality management processes. The findings demonstrate that systematic quality management of technical operations contributes to improved reliability of ship systems, supports safer vessel operation and strengthens the overall safety-oriented development of shipping.

Keywords: management; safety shipping; development; efficiency.

1. Introduction

Problem statement. The functional parameters of maritime transport as an object of economic analysis are interpreted through the prism of fundamental determinants defining the status of a state within the global architecture of maritime trade. The key indicators within this category include:

- external economic influence: the share of maritime transport in generating a surplus in the current account balance of the state's balance of payments;
- strategic autonomy: the level of transport (freight) independence of the state's foreign trade operations;
- resource potential: the aggregate deadweight tonnage of the fleet and its compliance with contemporary technical and economic standards;
- infrastructural capacity: the qualitative and quantitative characteristics of the fleet's carrying capacity and the throughput capacity of the state's port infrastructure;
- socio-labour dimension: the share of the national segment within the international maritime labour market.

The safety-oriented dimension is integrated into all levels of operational activity, encompassing navigational, environmental and cybersecurity components, which are critically important for the stable functioning of the maritime sector.

Safety-oriented maritime policy represents a strategic state approach to the governance of maritime activity in which priority is given to risk minimisation, the protection of national interests at sea and the safeguarding of the stability of the maritime environment (President of Ukraine, 2024).

Unlike a purely economic model, such a policy considers the sea not merely as a resource, but as a space that must remain free from military, environmental and criminal threats. The official use of the term "economic security" dates back to 1985, when the 40th Session of the United Nations General Assembly adopted the Resolution on "International Economic Security". At the 42nd Session a further step was taken through the adoption of the Concept of International Economic Security (United Nations General Assembly, 1985).

Methodology: The research is based on a qualitative literature review. Publications related to ship safety, technical operation quality and economic security were collected from Scopus, Web of Science, and Google Scholar. We focused on peer-reviewed journal articles and conference papers from 2015 to 2025. In total, 8 sources were reviewed. Inclusion criteria involved relevance to safety-oriented shipping and quality management; exclusion criteria removed non-peer-reviewed and redundant works. The selected articles were analyzed using comparative and synthesis methods to identify prevailing themes and models related to safety and quality in maritime operations.

Research Gap: Existing studies often treat maritime safety, vessel technical maintenance and economic factors in isolation. There is a lack of research on integrated approaches that combine multi-level safety systems with quality management frameworks. This study contributes to addressing this gap by conceptually linking safety-oriented shipping development with quality management principles, highlighting how improving technical operation quality enhances overall safety and operational efficiency. This joint perspective on safety and quality in vessel management has not been addressed in prior literature, constituting the novelty of our study.

2. Analysis of recent research and publications

Synthesising existing theoretical approaches, the concept of "economic security of an enterprise or industry" should be interpreted as an integral state of corporate resources (financial, human, information-technological and material-technical) together with entrepreneurial potential. This state must ensure the maximum efficiency of their utilisation in order to guarantee stable functioning, dynamic scientific and technological advancement and the prevention of critical threats.

An analysis of the architecture of economic security demonstrates the variability of its functional components depending on the specific characteristics of the operational environment of a business entity. Academic literature identifies several approaches to the classification of these components. In particular, the seven-component and extended model proposed by Donets and Vashchenko includes nine determinants by additionally incorporating economic and socio-political dimensions (Donets and Vashchenko, 2008).

As Yarova (2024) notes, under conditions of global digitalisation, the economic security of maritime enterprises is transforming from a passive resource protection mechanism into a proactive data management system. The author emphasises that the integration of CMMS and ERP modules is not merely a technical upgrade, but a critical prerequisite for minimising informational entropy and ensuring the resilience of shipping companies against external threats (Vorkunova, Yarova and Yarovyi, 2024). Research conducted by Lazakis and Velasco-Gallego (2022) demonstrates that the use of data-driven methods for identifying the operational states of ship systems in real time not only prevents accidents and emergency situations, but also significantly increases the operational profitability of maritime assets. This is achieved through a transition from scheduled maintenance to predictive service strategies, thereby minimising fleet downtime (Velasco-Gallego and Lazakis, 2022).

According to Kondratenko (2025), the strategic sustainability of maritime transport is currently based on proactive models of success management. The author argues that the balanced utilisation of shipping routes and the operational efficiency of cargo flow servicing are direct outcomes of effective quality management in the technical operation of vessels (Kondratenko, 2025).

Taking into account the specific characteristics of maritime enterprises, it is also necessary to consider studies devoted to the foundations of quality management systems in the technical operation of ships, which encompass a broad range of interconnected issues addressed by both foreign and national scholars. The theoretical basis for the development of innovative ideas and methodologies of technological management in the activities of shipping companies is comprehensively examined in the monograph by Malygin. The author focuses on strategies for mobilising resource potential and mechanisms for neutralising systemic contradictions.

Within the context of the vessel life cycle, effective management and strict compliance with customer requirements at the stages of ship design and construction create preconditions for integrating operational processes with future technical service algorithms, thereby forming the foundation of an effective quality management system for the technical operation of ships (Malygin, 2017).

3. Purpose of the study

The purpose of this research is to examine conceptual approaches to the development of safety-oriented shipping and to identify a multi-level safety system within the maritime industry based on quality management of the technical operation of vessels and the technical safety of navigation.

4. Presentation and substantiation of the main results

The process of identifying potential economic threats and developing an adequate system of countermeasures is highly complex, as it requires comprehensive knowledge of the problem under consideration.

The principal components of a safety-oriented maritime policy of the state include:

- national defence and sovereignty: protection of territorial waters, the exclusive economic zone and the safeguarding of the state maritime border;
- combating illegal activities: counteraction against piracy, terrorism, smuggling and illegal exploitation of marine biological resources;
- environmental safety: prevention of marine pollution, monitoring of water conditions and response to technological disasters;
- economic resilience: ensuring the safety and security of trade routes, ports and critical infrastructure, including cables, pipelines and offshore platforms;
- maritime safety: implementation of international standards (such as SOLAS and MARPOL), technical supervision of vessels and search and rescue operations.

The technical safety of navigation includes a range of factors that may be grouped into the following categories:

- structural integrity;
- ship systems and equipment, power installations, life-saving appliances (LSA) and communication systems (GMDSS);
- navigational safety: radar and ARPA systems, AIS (Automatic Identification System) and electronic chart systems (ECDIS);
- international standards, as technical safety is regulated by strict international conventions, including:
- SOLAS: the principal international instrument establishing minimum standards for ship construction and equipment safety;
- MARPOL: technical requirements aimed at preventing marine pollution caused by oil, sewage and waste;
- the International Safety Management Code (ISM Code): organisation of vessel technical maintenance in order to minimise accidents caused by human factors;
- technical supervision.

Figure 1 presents the mechanism of safety-oriented sustainable development of shipping, taking into account both controllable and uncontrollable factors influencing the functioning of the maritime sector.

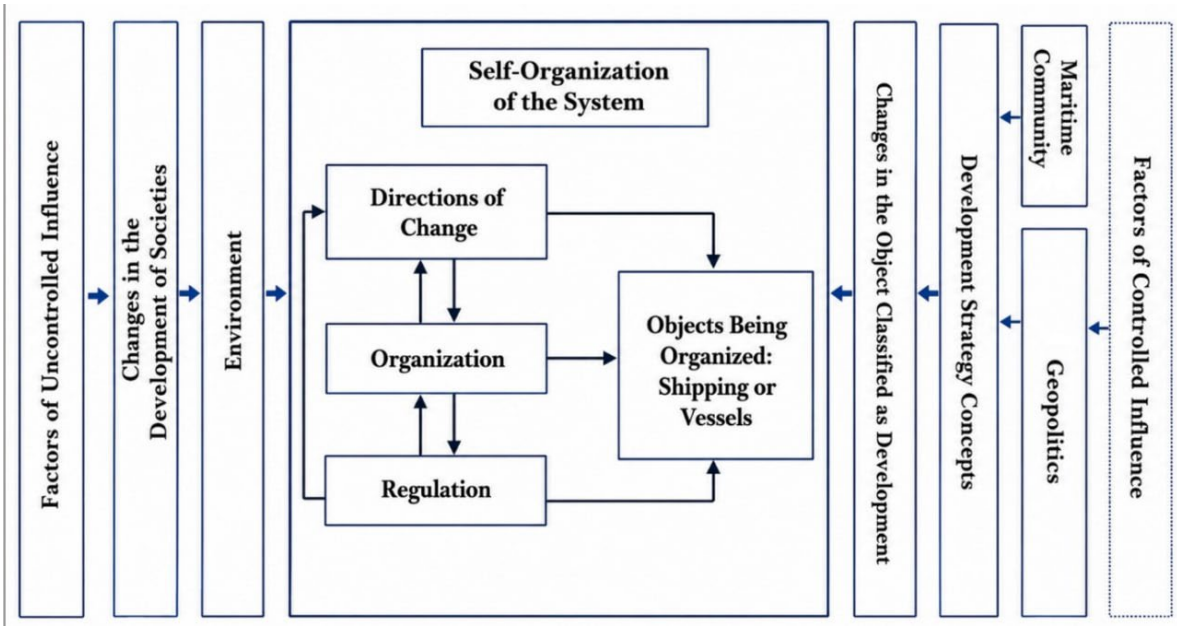


Figure 1. Mechanism of Safety-Oriented Sustainable Development of Shipping

This conceptual model illustrates the interaction between the maritime safety system and the vessel operation quality management system. The structure is based on international standards (e.g. the ISM Code) and ISO 9001 principles. It shows how safety requirements cascade from policy and regulatory levels down to operational procedures. The sources for this model include IMO guidelines and ISO standards for QMS in shipping (conceptual synthesis, verified against existing frameworks). Source: developed by the authors.

Using this mechanism as an example, it becomes evident that the influence of a wide range of factors determines the overall level of development of the maritime industry, its safety orientation and its strategic directions of development.

The transformation of global economic relations necessitates a reconsideration of approaches to the specialisation of national production subsystems towards the intensification of cooperative interaction. These tendencies lead to changes in the parameters of cargo transportability and impose new requirements on the technical and operational characteristics of merchant fleet vessels.

Under conditions of differentiated economic systems, merchant shipping, in addition to its purely commercial objectives and outcomes, fulfils a complex socio-economic function with a multiplier effect on the economies of individual states. Figure 2 presents the factors contributing to the development of global shipping.

Within the contemporary paradigm of transport and logistics technologies, the dominant priority is becoming the operational efficiency of cargo flow servicing and the maintenance of balanced utilisation of alternative transport routes.

Despite the dynamic nature of the market environment, two fundamental determinants remain critical to the competitiveness of shipping: the minimisation of average unit costs and the reduction of cargo transit time. The optimisation of these indicators constitutes a key condition for improving the efficiency of maritime transport within the global distribution system. For investors and operators, the priority remains the maximisation of commercial outcomes or the minimisation of risks across the phases of economic cycles. Consequently, under any condition of the global maritime trade market, the management of net cash flow within the accounting period becomes fundamental for ship owning and operating enterprises.

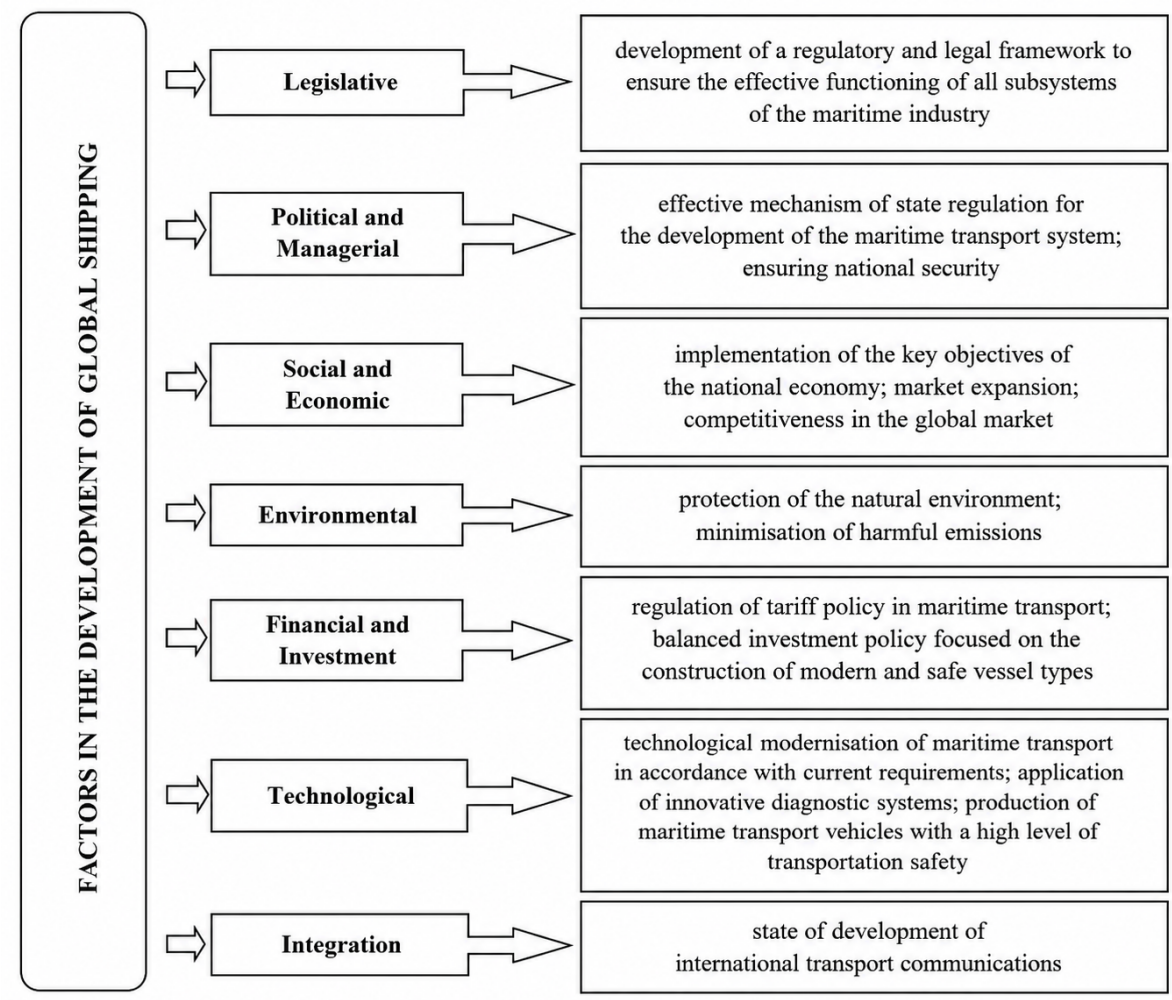


Figure 2. System of Factors Ensuring the Safety-Oriented Development of Shipping

This figure depicts our proposed safety-oriented development framework. It integrates safety principles (left side) with technical operation quality processes (right side). The logic comes from literature synthesis and best practices (see IMO safety guidelines and ISO QMS documents). We verified this model through expert discussions to ensure consistency with industry norms. Source: developed by the authors

At the same time, the image and competitiveness of fleets and ports are shaped by the perceived value from the perspective of cargo owners; however, at the current stage of development, the decisive factor is multi-level safety. For this reason, many developing countries at the initial stages of economic growth focused on the principles of gradual and safe integration into the maritime trade market. In merchant shipping, the medium-term period acquires particular significance within the system of development and operational activity. It is during this period that shipping companies must ensure the recovery of the market value of capital assets regardless of fluctuations in pricing parameters. Therefore, the management of the life cycle of any vessel should include two interrelated aspects: the dynamics of the rate of return and the accumulation and utilisation of depreciation funds and consequently the normalisation of induced investments (Kondratenko, 2025).

The progressive development of merchant fleet transport assets is characterised by a slower growth in vessel parameters and costs relative to increases in the productivity of capital assets. Only in the case of significant changes in environmental and quality standards may costs increase rapidly. In practice, this process is regulated by international maritime safety standards.

Among the key regularities of the development of the global maritime trade market, priority should first be given to the principle of equal participation of each state in shaping national maritime transport policy.

Subsequently, this process is implemented according to the level of awareness by the state of the role of the maritime industry in ensuring economic security and transport support for its strategy of participation in world trade.

Among the patterns of development of the maritime trade market, a special place is occupied by the orientation of leading shipowning structures towards achieving advantages based on economies of scale. This has become one of the principal directions of sustainable positioning strategies.

Contemporary quantitative characteristics of the global maritime trade market determine the tasks and directions for improving the development and functioning of fleets and ports. Alongside the optimisation of the technical and economic standards of vessels and cargo terminals, safety orientation assumes a particularly significant role.

The technical and technological safety of vessels represents a complex of structural, mechanical and operational measures ensuring that a ship is capable of withstanding navigational loads, protecting the crew and cargo and avoiding harm to the environment.

The category of vessels with minimal technical risk includes modern tankers, gas carriers and container ships. For bulk carriers, however, safety issues remain relevant to a certain extent.

In our view, technical and economic safety constitute the key components of the systemic safety of shipping. The definition of shipping safety is outlined in the Regulations on the Safety Management System for Maritime and Inland Waterway Transport, according to which it is interpreted as a state of preservation and protection of human health and life, the environment and property at sea and on inland waterways, as well as the absence of unacceptable risks associated with death or injury to people, environmental damage or material losses (Cabinet of Ministers of Ukraine, 2024).

The systemic safety of shipping possesses a complex multi-level structure and ensuring its functioning represents a highly challenging process for all maritime states and for the global maritime industry as a whole.

According to the standards of the International Maritime Organisation, modern vessels are required to be equipped with technical systems capable of providing the level of automation prescribed by international conventions. At present, specialised software is being developed to further increase this level. Software systems currently undergoing testing are capable of collecting and processing data and making informed decisions aimed at minimising human error. Such systems are expected to be used both on navigation bridges and in engine rooms. Consequently, the implementation of innovations in the contemporary development of maritime and inland waterway shipping is not merely a modern trend, but an essential component enabling newly constructed vessels to comply with the standards and conventions of the International Maritime Organisation (IMO, 1974; IMO, 1993). The factor underlying these innovations is of paramount importance – namely, the safety of human life.

5. Economic justification

Effective maintenance management reduces unplanned downtime and repair costs in shipping. Preventive and predictive maintenance improve vessel availability and reliability. According to Velasco-Gallego and Lazakis (2022), predictive maintenance strategies reduce downtime and improve operational efficiency by enabling condition-based maintenance decisions. These improvements contribute to lower lifecycle costs and higher vessel availability. This proactive approach not only minimizes downtime but also extends the lifespan of maritime equipment. By anticipating failures and scheduling maintenance only when necessary, companies achieve significant cost savings and avoid expensive emergency repairs. Such improvements in operational efficiency and safety translate into higher economic security for shipping operations.

6. Conclusion

Under contemporary conditions, the development and implementation of a stable quality management system for the technical operation of vessels appears strategically justified, with the objective of minimising the entropy of managerial processes. The implementation of this concept is determined by a number of fundamental prerequisites, namely:

- optimisation of supply chains: the formation of a pool of a limited number of verified suppliers in order to ensure the guaranteed reliability of resource provision;
- informational precision: the availability of verified data concerning the current technical and operational condition of ship systems and the development of highly accurate predictive models of their short-term functioning;
- digital transformation of management: the integration of highly reliable telecommunication networks and specialised software, including CMMS (Computerised Maintenance Management System) and EAM (Enterprise Asset Management) systems, as well as specialised ERP modules;
- process automation: the implementation of automated management algorithms and the deterministic simplification of operational marketing and procurement procedures for material and technical resources;
- managerial convergence: ensuring a high level of coordination across all hierarchical levels of vessel operation based on a unified centralised data repository.

The systematic implementation of the proposed safety-oriented approach ensures the extension of the operational life cycle of ship equipment, the intensification of fleet utilisation and increased transparency of accounting processes while simultaneously optimising fixed assets. The implementation of this strategy contributes to a substantial reduction in unit operational costs, growth in the productivity of maritime human resources within predetermined risk levels and guarantees a high degree of technical reliability together with the timeliness of logistical support. Taken together, these factors contribute to a more effective quality management framework for the technical operation of vessels and strengthen the overall safety of shipping at the global level.

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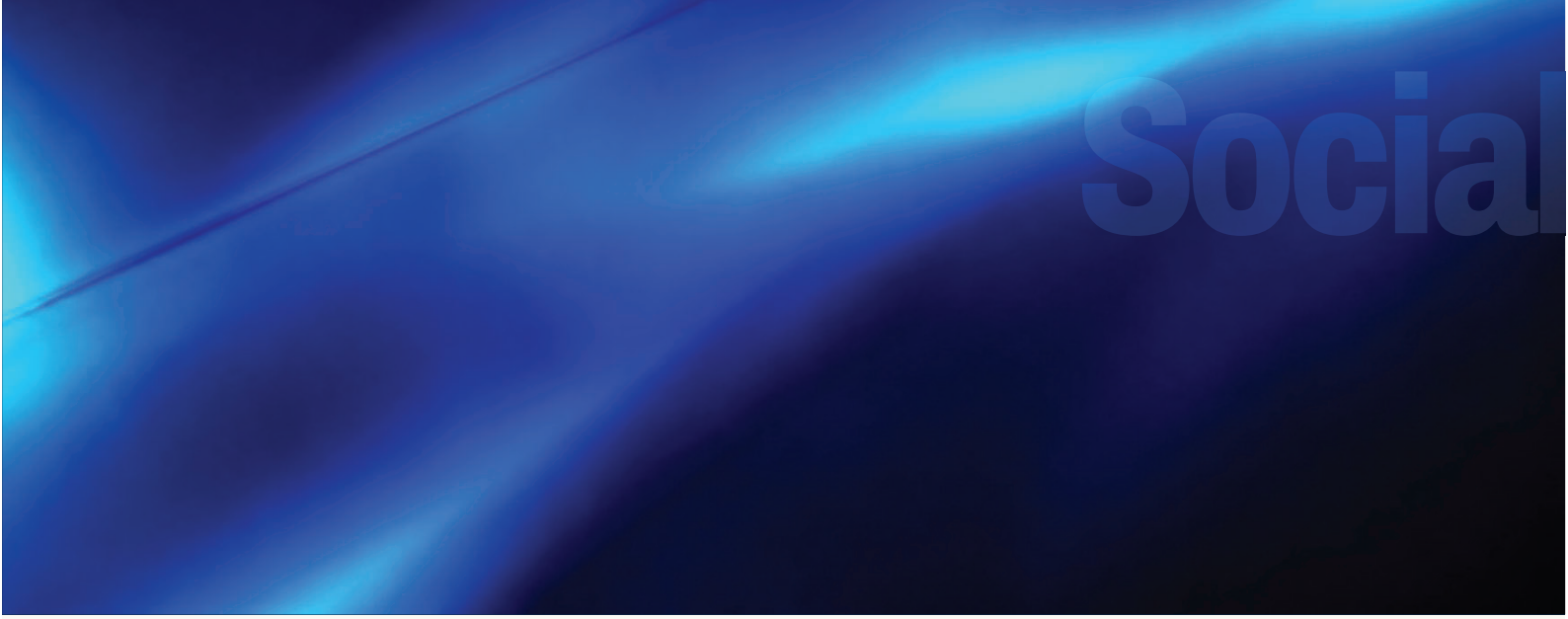
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Towards a Human-Centred Framework for AI-Based Maritime Training Implementation: Evidence from a PRISMA Review

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Abstract: Artificial intelligence (AI) has increasingly been applied within Maritime Education and Training (MET), enabling personalised learning, real-time performance feedback, and adaptive training environments. However, adoption in real-world settings remains constrained by the safety-critical nature of the sector, concerns regarding pedagogical validity, and the need for alignment with certification frameworks such as the STCW Convention. Although relevant reviews exist, the evidence remains dispersed across technologies, methods, and institutional contexts, with no study adequately addressing the practical conditions that hinder or enable AI implementation in MET. This study addresses that gap through a systematic literature review conducted in accordance with the PRISMA protocol, analysing 34 peer-reviewed articles published between 2016 and 2026. The review identifies key barriers and critical success factors for AI adoption and proposes an actionable framework linking barriers, enablers, and recommended actions to support sustainable AI integration in maritime training — with implications for practitioners, policymakers, and researchers. Notably, organisational barriers emerged as the most prevalent impediment to AI adoption (n = 20; 58.8%), followed by technical and data-related constraints (n = 19; 55.9%), indicating that the primary obstacles to AI integration are rooted in institutional culture and governance rather than technology alone.
Keywords: Maritime Education and Training (MET); Artificial Intelligence (AI); Technology Adoption; Critical Success Factors (CSF); Implementation Challenges.

1. Introduction

The maritime industry has long adapted to technological change, with digitalization and automation now reshaping operations (Meštrović et al., 2024). The emergence of Shipping 4.0 and Maritime Autonomous Surface Ships (MASS) demands a new professional profile—the "Seafarer 4.0"—equipped with both Science, Technology, Engineering, and Mathematics (STEM) skills and humanistic competencies (Simmons and McLean, 2020). However, the regulatory framework lags behind: the Standards of Training, Certification and Watchkeeping (STCW) Convention has not seen substantial updates since the 2010 Manila Amendments (Türkistanli, 2024), creating a dangerous gap between operational reality and certification requirements (Meštrović et al., 2024).

Safe and efficient shipping depends on a skilled workforce, and simulators have proven effective for risk-free, cost-efficient training (Tusher et al., 2023). The COVID-19 pandemic accelerated the shift to e-learning, where Adaptive Instructional Systems (AIS) powered by AI enable learner-centred models, though they face challenges such as "small data", addressed by techniques like Decision Trees and K-Nearest Neighbours (Karimi et al., 2024). Generative AI offers promising applications for competency assessment, moving beyond static multiple-choice tests to dynamic, scenario-based evaluations aligned with Convention on the International Regulations for Preventing Collisions at Sea (COLREG) rules (Kizilay and Çelik, 2025). Moreover, attention to affective outcomes—motivation, confidence, attitude—and the use of neurophysiological metrics (e.g., eye-tracking, Electroencephalogram (EEG), Electrocardiogram (ECG)) is emerging as essential to objectively measure cognitive load and situational awareness during simulator training (Tusher et al., 2023; Türkistanli, 2024). Despite these possibilities, AI adoption in authentic Maritime Education and Training (MET) settings remains limited due to stringent demands for reliability, pedagogical validity, and compliance with professional certification requirements (Ibrahim, 2024). Although relevant reviews exist, evidence remains dispersed. Some

offer overarching perspectives on digital tools (Türkistanli, 2024); others focus narrowly on adaptive instructional systems for safety training (Karimi et al., 2024). None adequately address what hinders and enables AI implementation in real-world MET contexts. Therefore, this study conducts a Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) -based systematic review to identify barriers and critical success factors (CSFs) for scaling AI solutions in maritime training.

2. Methodological Approach

To address the identified research gap, a systematic literature review was conducted following the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), chosen for its capacity to ensure transparency and reproducibility in the reporting of systematic reviews (Paraskevas et al., 2024). The review process was structured according to four sequential phases — Identification, Screening, Eligibility, and Inclusion.

In the Identification phase, a systematic search was conducted across five major electronic databases — Scopus, IEEE Xplore, Web of Science, ScienceDirect, and DOAJ — selected for their extensive coverage of peer-reviewed literature across multiple disciplines. The search string combined MET-related descriptors, including maritime education and training, seafarer training, and STCW, with AI-related terms such as machine learning, deep learning, learning analytics, intelligent tutoring systems, chatbots, and generative AI, amongst others. The initial search yielded 476 records following the removal of duplicates, with a considerable degree of overlap observed across databases, reflecting the multiple indexing of leading journals in the field. Records were subsequently screened against predefined eligibility criteria, excluding studies published outside the 2016–2026 timeframe (n = 41), non-peer-reviewed publications (n = 47), and records not written in English (n = 14), yielding 388 records for subsequent screening.

In the Screening phase, titles and abstracts of the 388 records were assessed against the inclusion criteria is *Maritime Context, Central use of AI,* and others. Studies were required to address a clearly defined maritime context with substantive AI integration, provide empirical or literature-based evidence, and demonstrate relevance to real-world MET implementation. This resulted in the exclusion of 321 records, with 67 studies advancing to full-text assessment. In the Eligibility phase, the 67 full texts were evaluated against criteria such as: limitations associated with availability, challenges linked to users' skills, etc., with particular emphasis on relevance, methodological transparency, and applicability to AI adoption in MET. Studies were excluded when they lacked a clearly defined maritime context, substantive AI integration, or a discernible training component. Following this assessment, 33 studies were excluded, yielding a final corpus of 34 articles.

Data analysis followed the three-stage thematic synthesis approach. In the first stage, each of the 34 selected studies was read in full and coded line-by-line using a structured extraction form, capturing research objectives, type of AI technology, reported outcomes, stakeholder perspectives, and recommendations. Coding was conducted manually and independently by all four authors. In the second stage, descriptive codes were compared and grouped into initial descriptive themes. In the third stage, these descriptive themes were interpreted and refined inductively — without a pre-defined category scheme — yielding the five overarching dimensions reported in the findings: Technical and Data-Related, Human Factors, Infrastructure, Organisational, and Regulatory. Inter-coder agreement was ensured through iterative discussion among the four authors until consensus was reached on all thematic groupings.

In the Inclusion phase, the 34 selected studies were subjected to thematic synthesis, with findings systematically categorised into barriers and critical success factors, distinguishing between institutional MET contexts and corporate or industry settings.

3. Findings of Systematic Literature Review

3.1. Bibliometric Data

The systematic search, covering the period from 2016 to 2026, returned a final corpus of 34 peer-reviewed studies. No eligible studies were identified for the 2016–2019 period, reflecting an incipient field in which AI applications within MET had not yet generated a sufficient body of peer-reviewed work. From 2020 onwards, a steady but modest growth became apparent: two publications were recorded in 2020, rising to four in 2021, before stabilising at two per year in both 2022 and 2023. This exploratory phase saw researchers begin to

investigate the potential of AI tools — particularly in simulator-based training and performance assessment — without yet producing the volume or diversity of work that would characterise a maturing field.

A clear inflection point emerges in 2024, with eight publications recorded, followed by a peak of 16 studies in 2025. This exponential surge coincides with the widespread availability of large language models and generative AI tools, the increasing integration of AI into high-fidelity maritime simulators, and the growing urgency to align training frameworks with the competency demands of autonomous shipping. Taken together, these developments appear to have transformed AI in MET from a niche academic interest into a rapidly consolidating area of maritime research.

Regarding the dissemination of knowledge, Applied Sciences (MDPI) emerges as the leading publication outlet with five articles, followed by TransNav and the International Journal on Marine Navigation and Safety of Sea Transportation, each contributing three studies. The presence of journals such as Cognition, Technology & Work and WMU Journal of Maritime Affairs reflects the inherently interdisciplinary character of the field, spanning engineering, cognitive sciences, and maritime policy.

The methodological profile of the selected studies reveals a field increasingly grounded in empirical investigation. Of the 34 studies included, 22 (64.7%) adopt an empirical approach, drawing on experimental designs, simulator-based studies, surveys, pilot programmes, and computational modelling. A further 10 studies (29.4%) are conceptual, encompassing systematic reviews, bibliometric analyses, and theoretical frameworks, while the remaining two (5.9%) combine both orientations through mixed-method designs. This distribution indicates that, despite its relative youth, research on AI in MET has already moved beyond the purely theoretical stage. The predominance of empirical work reflects a growing commitment to testing AI-based tools in realistic training environments, while the continued presence of conceptual studies highlights the ongoing need to synthesise fragmented knowledge and provide coherent frameworks for practice and future investigation. Taken together, these findings portray a field that is young but accelerating, empirically driven, and increasingly interdisciplinary.

3.2. Barriers to AI-Based Maritime Training

This section synthesises the principal barriers identified across the corpus, grouped into five thematic categories: Technical and Data-Related (n=19/ 55.9%), Human Factors (n=15/ 44.1%), Infrastructure (n=9/ 26.5%), Organisational (n=20/ 58.8%), and Regulatory Barriers (n=12/ 35.3%). Together, these categories encompass the multidimensional challenges that researchers, educators, and institutions face when attempting to embed AI solutions within MET contexts.

The barriers documented across the five categories are deeply interconnected rather than independent. Technical limitations in data quality and AI system design constrain the development of robust tools (Fan and Yang, 2023; Karimi et al., 2024; Xue et al., 2024); human factors barriers impede adoption even where technically adequate solutions exist (Sharma and Nazir, 2021; Bartusevičienė and Valionienė, 2021); infrastructure deficiencies restrict deployment in resource-limited and offshore contexts (Smith et al., 2020); organisational inertia slows the curricular transformation needed to embed AI in training practice (Mori, 2025; Ahmad Fuad et al., 2025); and regulatory frameworks, anchored to pre-AI competency paradigms, fail to provide the normative guidance required to legitimate AI integration in MET (Chan et al., 2025; Westin and Lundberg, 2025). This multi-layered structure reflects the broader challenge of implementing emerging technologies in highly regulated, safety-critical industries, and suggests that effective AI integration will require coordinated action across technical, educational, organisational, and regulatory domains simultaneously.

Many of the barriers identified are not unique to MET but represent challenges documented more broadly in the literature on AI adoption in professional and safety-critical education. What distinguishes the maritime context is a particular combination of factors: a strongly internationalised regulatory environment, a workforce characterised by cultural and linguistic diversity and constrained connectivity, and an accelerating technological transition driven by MASS and digital transformation that is simultaneously generating new competency demands and disrupting established structures of professional practice (Simmons and McLean, 2020; Meštrović et al., 2024; Ahmad Fuad et al., 2025). These contextual specificities amplify the generic barriers to AI adoption and underscore the urgency of the research and policy agenda they imply.

3.3. Critical Success Factors

The literature identifies a comprehensive set of critical success factors supporting the effective implementation of AI-based maritime training, grouped into five main categories: technical success factors (n = 19; 55.88%), human factors enablers (n = 10; 29.41%), organisational enablers (n = 17; 50%), regulatory and policy enablers (n = 10; 29.41%), and infrastructure enablers (n = 10; 29.41%).

Technical success factors centre on data quality and availability, system interoperability, and the robustness of AI models — elements that are fundamental to reliable system performance and effective integration with existing training platforms (Xue et al., 2024; Jiang and Fan, 2025). Without high-quality data and interoperable architectures, the effectiveness of AI applications in maritime training remains significantly constrained (Sharma et al., 2022; Westin and Lundberg, 2025). Human factors enablers are equally critical, particularly regarding digital literacy, user acceptance, and continuous professional development. The success of AI-based training environments depends heavily on users' ability to interact with and trust these systems (Sharma and Nazir, 2021; Ibrahim, 2024), as well as on user-centred design approaches that align technological solutions with human needs (Hristova et al., 2024; Karnavas et al., 2025).

At the organisational level, critical success factors are strongly linked to strategic alignment, leadership commitment, and institutional readiness for change. METIs that embed AI within their strategic vision and adapt their training programmes accordingly are better positioned to benefit from these technologies (Simmons and McLean, 2020; Fan and Yang, 2023), with governance structures and change management capabilities identified as essential for long-term sustainability (Tusher et al., 2023; Türkistanli, 2024). Regulatory and policy enablers provide the structured framework within which AI adoption can occur responsibly, with clear guidelines, standardisation mechanisms, and ethical frameworks ensuring compliance and trust — particularly relevant in a sector where regulatory conformity is central to training and certification (Kizilay and Çelik, 2025; Baradziej, 2025; Meštrović et al., 2024). Finally, infrastructure enablers — encompassing advanced technological infrastructure, access to simulation environments, and computational capacity — are identified as a prerequisite not only for implementation but also for scalability (Pei et al., 2024; Mori, 2025; Munim et al., 2025).

3.4. Practical Framework for AI Implementation in Maritime Education and Training

After analysing the main barriers and CSFs, the present framework is structured (Table 1). This structure recognises that the adoption of AI in maritime training is not a purely technical challenge, but a multidimensional process that requires simultaneous attention to people, institutions, regulation, and resources (Ibrahim, 2024; Sharma et al., 2022; Meštrović et al., 2024).

From a theoretical perspective, the framework offers three contributions to the existing literature. First, it establishes a clear link between barriers and CSFs, showing how each facilitating condition can be understood as a direct response to a specific obstacle. This is an important step forward, as earlier studies in the field have tended to list barriers and enablers separately, without explaining how they relate to one another (Simmons and McLean, 2020; Lisowski, 2021). Second, the framework introduces a temporal dimension by classifying recommended actions according to their implementation horizon — short-, medium-, or long-term. This is particularly useful for Maritime Education and Training Institutions (METIs) and bodies such as the IMO, where decisions must be sequenced and resources allocated carefully over time. Third, by specifying which actors are responsible for each dimension — whether MET institutions, shipping companies, flag states, or intergovernmental organisations — the framework helps clarify who should lead each type of intervention.

One finding that deserves particular attention is the distinctive nature of the Regulatory & Policy dimension. Unlike the other four dimensions, where METIs can take direct action, regulatory barriers largely fall outside the control of individual institutions. The growing mismatch between current STCW requirements and the competency demands of AI-enabled and increasingly autonomous vessels (Baradziej, 2025; Park et al., 2025) can only be addressed through coordinated international action. The framework makes this distinction explicit, which is relevant not only for researchers but also for practitioners seeking to understand the limits of what institutions can achieve on their own. Overall, the proposed framework offers a practical and theoretically grounded tool to support both future research and institutional decision-making. It provides a shared structure

Table 1. Integrative Framework for Sustainable AI Adoption in Maritime Education and Training (MET).

Dimension	Context	Barriers	Critical Success Factors (CSFs)	Recommended Actions	Time Horizon
Technical & Data	*MET institutions & AI developers*	Scarcity and low quality of data for training/operating AI systems in maritime contexts	Data quality assurance and pre-processing (Smith et al., 2020; Xue et al., 2021)	Establish shared anonymised maritime data repositories between METIs and industry	**Short-term (<1 yr)**
		Technical complexity of model validation and benchmarking (simulators, biosignals, LLMs)	Small-data strategies: RAG, transfer learning, synthetic data (Karimi et al., 2024; Baradziej, 2025)	Develop standardised pre-processing pipelines for biosignals and simulator logs	**Short-term (<1 yr)**
		Limited model robustness and generalisation with small, domain-specific datasets	Real-world operational data for model calibration – AIS, logs (Hwang and Youn, 2022)	Apply transfer learning and RAG techniques to overcome data scarcity in MET	**Medium-term (1–3 yrs)**
		Poor interpretability of AI outputs reducing instructor and regulator trust	Model interpretability and explainability – XAI / SHAP (Jiang and Fan, 2025; Pei et al., 2024)	Embed XAI tools (e.g. SHAP) in automated assessment reports for instructors	**Medium-term (1–3 yrs)**
			Rigorous benchmarking aligned with STCW standards (Xue et al., 2021; Mraković et al., 2025)	Define STCW-aligned validation protocols and benchmarks for AI training systems	**Long-term (>3 yrs)**
Human Factors	*Instructors, cadets & seafarers*	Resistance and low acceptance of AI among instructors and trainees	Instructor digital competence and continuous professional development (Sharma and Nazir, 2021)	Launch structured AI-pedagogy training programmes for MET instructors	**Short-term (<1 yr)**
		Insufficient digital literacy and technological competence of MET instructors	User-centred and participatory design processes (Sharma et al., 2022; Hristova et al., 2024)	Introduce AI/LLM literacy modules for cadets at the start of training	**Short-term (<1 yr)**
		Distrust in AI outputs and ambiguity about the human vs. automated role	Digital and AI literacy among maritime professionals (Li and Wang, 2025; Ibrahim, 2024)	Engage instructors and trainees in co-design of AI tools from prototype stage	**Medium-term (1–3 yrs)**
		Concerns over privacy and biometric monitoring of trainees	Human–AI complementarity: AI augments, not replaces, expertise (Ibrahim, 2024; Tusher et al., 2023)	Develop clear institutional policies on biometric and performance data use	**Medium-term (1–3 yrs)**
			Integration of behavioural competencies and situational awareness (Chan et al., 2025)	Rebalance curricula to strengthen behavioural and automation-management competencies	**Long-term (>3 yrs)**

Organisational	*METIs, shipping companies & flag states*	Curricular rigidity and difficulty redesigning programmes aligned with AI	Institutional culture of innovation and long-term strategic planning (Simmons and McLean, 2020)	Form METI–industry working groups to co-define AI-competency profiles for seafarers	**Short-term (<1 yr)**
		Absence of institutional strategy and committed leadership for digital transformation	Structured industry–academia collaboration (Bartusevičienė and Valionienė, 2021; Campos et al., 2025)	Conduct small-scale AI pilot projects before full institutional deployment	**Short-term (<1 yr)**
		Gaps in ethical governance, data privacy and accountability frameworks	Curriculum integration and pedagogical redesign (Lisowski, 2021; Türkistanli, 2024)	Revise curricula to explicitly embed AI, MASS and automation competencies	**Medium-term (1–3 yrs)**
		Insufficient structured collaboration between METIs, industry and technology providers	Gradual and phased AI implementation (Ibrahim, 2024; Sharma et al., 2022)	Establish ethics and data-privacy committees within METIs for AI oversight	**Medium-term (1–3 yrs)**
			Ethical governance and data privacy frameworks (Hristova et al., 2024; Kizilay and Çelik, 2025)	Build international METI consortia for knowledge transfer and good-practice sharing	**Long-term (>3 yrs)**
Regulatory & Policy	*IMO, flag states & classification societies*	STCW framework outdated relative to AI and autonomous shipping (MASS) requirements	Alignment with STCW and IMO model course frameworks (Lisowski, 2021; Baradziej, 2025)	Map incompatibilities between existing AI systems and current STCW requirements	**Short-term (<1 yr)**
		Absence of standards for AI-mediated or AI-assisted competency assessment	Regulatory modernisation and normative adaptation (Türkistanli, 2024; Park et al., 2025)	Propose amendments to IMO model courses to recognise AI-assisted assessment	**Medium-term (1–3 yrs)**
		Uncertainty over regulatory recognition of AI-supported training and certification	Engagement with policy processes and regulatory advocacy (Meštrović et al., 2024; Campos et al., 2025)	Participate actively in IMO working groups on MASS and digital competencies	**Medium-term (1–3 yrs)**
		Slow pace of normative revision relative to the speed of technological change		Develop an international regulatory framework for AI-mediated MET certification	**Long-term (>3 yrs)**
Infrastructure	*METIs, ports & shipping companies*	Insufficient digital connectivity and infrastructure at METIs, especially in developing countries	Adequate maritime digital infrastructure and connectivity (Li and Wang, 2025; Meštrović et al., 2024)	Audit digital infrastructure gaps across METIs, prioritising developing-country institutions	**Short-term (<1 yr)**
		High acquisition and maintenance costs for high-fidelity simulators and AI platforms	Integration of AI tools with existing simulation platforms (Sharma et al., 2022; Bokau et al., 2025)	Develop open APIs and standard formats for AI module integration with MET simulators	**Medium-term (1–3 yrs)**
		Limited interoperability between AI tools and existing training simulation systems	Hybrid onboard and shore-based training models (Mori, 2025; Campos et al., 2025)	Create shared-funding models (PPPs, EU grants) for AI infrastructure in MET	**Medium-term (1–3 yrs)**
		Scarcity of onboard training berths and over-reliance on shore-based models	Sustainable funding and resource allocation for AI adoption (Ibrahim, 2024; Sharma and Nazir, 2021)	Implement hybrid programmes combining AI-enhanced simulation with validated onboard training	**Long-term (>3 yrs)**

MASS = Maritime Autonomous Surface Ship; STCW = Standards of Training, Certification and Watchkeeping; PPP = Public–Private Partnership; RAG = Retrieval-Augmented Generation; XAI = Explainable Artificial Intelligence.

for comparing AI adoption processes across different METIs and regulatory contexts, and encourages dialogue between maritime educators, technology developers, and policy-makers.

4. Conclusion

The systematic analysis of the literature reveals that AI adoption in Maritime Education and Training (MET) is a rapidly expanding, empirically driven, and increasingly interdisciplinary field, characterized by a significant acceleration from 2024 onwards. The findings confirm that AI adoption in MET is a multidimensional challenge. Barriers span technical, human, organisational, regulatory, and infrastructural dimensions, and are deeply interconnected: addressing one layer in isolation is unlikely to produce sustainable outcomes. Organisational barriers emerge as the most pervasive (n = 20; 58.8%), followed by technical and data-related constraints (n = 19; 55.9%), underscoring that the primary obstacles to AI integration are not purely technological but are rooted in institutional culture, curricular rigidity, and governance gaps. The integrative framework proposed in this review responds directly to these challenges by linking barriers, CSFs, and recommended actions within a structured, actor-specific, and time-sensitive model. Its key contribution lies in making explicit what the literature has largely left implicit: that different dimensions of AI adoption require different actors, different timescales, and different types of intervention. In particular, the Regulatory & Policy dimension stands apart, as its resolution depends on coordinated international action — notably through the IMO — rather than on institutional initiative alone. Several limitations should be acknowledged. The review is restricted to English-language peer-reviewed publications, which may underrepresent contributions from non-Anglophone MET contexts. Furthermore, the proposed framework has not yet been empirically validated, and future research should prioritise actions with MET experts and longitudinal case studies tracking AI adoption trajectories across diverse institutional settings. Comparative studies examining adoption patterns across flag states and regulatory jurisdictions would further strengthen the evidence base.

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Mother Tongue Interference among Croatian ESP Students: The Example of Maritime English

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Abstract: Learning English as a Foreign Language (EFL) presents various challenges for Croatian learners, including the students attending Maritime English (ME) classes at the Faculty of Maritime Studies in Split. Due to significant differences between Croatian and English grammar rules, students often tend to make systematic errors that affect their overall language skills and may eventually affect communication, safety of navigation, efficiency and daily operations in various branches of the maritime industry in which they intend to pursue careers. This study uses a mixed-methods approach that embraces cognitive, observational and empirical methods (e.g. testing and in-class activities), contrastive analysis, qualitative data analysis and description, in order to highlight the key pronunciation, spelling, syntax, and vocabulary areas where Croatian students make common errors that are largely influenced by the differences between the two languages. Understanding these challenges and addressing these errors through targeted teaching strategies (focused practice, contrastive analysis and clear explanations) can prevent or mitigate negative mother tongue transfer and significantly improve students' accuracy, fluency and confidence in English communication.

Keywords: EFL; ESP; Maritime English; Croatian students; mother tongue interference

1. Introduction

Learning English as a Foreign Language (EFL) presents various challenges for Croatian students due to significant differences between Croatian and English language rules. The so-called interference is a linguistic phenomenon that typically consists of using the patterns of the mother tongue that do not correspond to the target language (Halahan et al., 2022). As a result, many learners tend to make systematic errors that affect their overall communication skills. It is essential for educators – especially those at maritime schools – to identify and understand these common errors in order to develop effective teaching strategies that address specific learner needs. English is vital in the maritime industry as it serves as the international language for navigation, emergencies and daily operations at sea and ashore (Skračić et al., 2026). The safety at sea, the efficiency of global trade and the marine environment may be put at risk by EFL learners whose Maritime English contains mistakes arising from the negative mother tongue interference (MTI). Both teachers and learners are aware that making mistakes is an integral part of the learning process. Still, using English language inside their classroom is a known challenge for learners as they are concerned about being judged by their teachers and peers (Irene, 2023). That is why the above mentioned teaching strategies addressing specific needs should include a soft approach. If the students feel uneasy or anxious about using English in class, tomorrow they will experience the same foreign language anxiety at work – and make more mistakes in the process.

2. Research methodology

To achieve the set goals, the study was conducted through a mixed-methods approach. Empirical methods, such as surveys, testing, assignments, video and live presentations and in-class activities, which had been observed over a period of ten years, were used in order to identify and clarify the errors resulting from negative mother tongue interference. The methodology then included qualitative data analysis, i.e. observational and comparative approaches focusing on lexicosemantic and grammatical features of Croatian and English, and their mutual influence in the language learning process. Contrastive analysis was particularly useful in explicitly explaining and comparing English and Croatian grammatical structures, in raising learners' awareness of the

differences and, eventually, in preventing or mitigating negative MTI errors. The latter have been distributed into the following categories: Pronunciation / Spelling, Grammar, and Vocabulary.

3. Detected MTI errors

3.1. Pronunciation and spelling

Mother tongue interference (MTI) causes the mispronunciation of many English words. For example, difficulties occur when it comes to English sounds not present in Croatian, such as the "th" sound (/θ/, /ð/). The voiceless /θ/ as in *think* is usually pronounced correctly, although not effortlessly, whereas the voiced /ð/ (as in *the*, *that*) is typically pronounced as /d/. The "ch" is sometimes pronounced incorrectly due to MTI, e.g. in words *mechanical* or *archipelago*: /h/ instead of /k/. The wrong pronunciation of "au" is detected across all maritime student population: /au/ instead of /ɔ:/ in words like *automatic* or *nautical*. Quite curiously, their pronunciation of the words *Australia*, *autumn* or *fault* is accurate.

As for spelling, probably the best example is the capitalisation of proper adjectives (adjectives derived from proper nouns such as nationalities and languages). While English capitalises proper adjectives, many other languages, including French, Italian, Spanish, Portuguese, Russian or Croatian do not capitalize them. Expectedly, many students at the Faculty of Maritime Studies in Split will typically fail to capitalise the proper adjectives (e.g. *an *italian port*, *many *japanese ships*) unless they happen to be at the very beginning of a sentence (*Japanese training vessels are well-equipped*).

These errors can be easily eliminated by explaining rules – which are very consistent in this language area. A teacher's soft approach including repeated short exercises is likely to improve students' performance (Skračić et al., 2026).

3.2. Grammar

3.2.1. Syntax

While English, French and many other languages generally follow the Subject-Verb-Object (SVO) order, other languages may apply a different syntax or may use a more flexible sentence structure. For example, Japanese sentences generally feature an SOV structure (Muliana & al, 2025). According to a linguistic typology given by Herceg (2019), Croatian is classified as an SVO (Barić & al, 2026). However, Croatian features a number of inflections (changes in word form), affixes, and a complex case system, which allows a sentence to be structured in various ways, without losing the meaning. Here is an example: *Ta oluja je uništila luku Gulfport*. (SVO); *Luku Gulfport je uništila ta oluja*. (OVS); *Uništila je ta oluja luku Gulfport*. (VSO); *Uništila je luku Gulfport ta oluja*. (VOS). All versions are correct and acceptable, the only difference being the emphasis on the subject, the object or the action itself. In English, the SVO version is the only correct and acceptable option: *That storm destroyed the port of Gulfport*. This is why Croatian students are in some cases confused when constructing their English SVO sentences. In reported speech, a common error is to say **The skipper asks is the boat ready to set sail*. The correct form for a question embedded in another clause or reported speech is: "*The skipper asks if / whether the boat is ready to set sail*", following the normal SVO sentence structure (Aarts, 2011). Overly literal translation from Croatian is likely to result in unnatural or incorrect phrasing. To avoid such mistakes, students must be taught from the very beginning not to translate every word, word by word, but to express the meaning and concept immediately in a foreign language (Halahan et al, 2022), omitting or adding the words, or changing their sequence when necessary.

Many Slavic languages including Croatian allow multiple negative words, while English syntax does not allow double or more negatives within a sentence (Dankić and Karadža, 2011). The translation of the Croatian sentence *Ona nikada ništa nikome nije rekla* (four negatives) would be *She has never said anything to anyone*. Once the negative word "never" is introduced, all other words remain positive. Students tend to avoid errors in this area, despite the popular culture products (films and songs) where statements like **She doesn't know nothing* can be heard.

3.2.2. Tenses

In the English language, progressive tenses (also called continuous tenses) show actions that are unfinished or ongoing. They emphasise an uninterrupted duration or an action in progress at a specific time, unlike simple tenses which focus on completed actions, habits or states (Aarts, 2011).

When there is an equivalent progressive tense in the Croatian language (e.g. in the past), students do not make mistakes: *The Titanic was sinking = Titanic je tonuo*, *The Titanic sank = Titanic je potonuo*. Intuitively, Croatian students will correctly say *Now I know what you mean* instead **Now I'm knowing what you are meaning* – probably they have heard the correct expression a number of times at school, in films and in popular songs. However, there is a lack of examples offering explanations regarding the nuances or exceptions. Verbs that describe mental states / cognition (*understand*, *recognize*, *forget*, *think…*), emotions / feelings (*love*, *dislike*, *hate*, *want*, *feel…*), senses (*smell*, *taste*, *feel…*), and possession / association (*own*, *possess*, *belong…*) often prefer simple tenses but can also function well in continuous tenses. Teachers should underline that some of these verbs can be found in both types of tenses, with minor or major differences in meaning: "*How do you feel?*" / "*How are you feeling*"; "*Marko thinks he will change his job*" / "*Marko is thinking about changing his job*". Both options have the same form in the Croatian language; therefore, it is important to remind the students to be careful when forming sentences or translating them because, for example, "*Marko is thinking about...*" is used for active, ongoing thought or consideration, while "*Marko thinks...*" is used for opinions, beliefs, or quick judgments.

The real problems occur when using Present Simple, Present Continuous, Present Perfect Simple and Present Perfect Continuous: they offer nuances that do not exist in Croatian language (Skračić et al., 2026). When a group of seafarers attending a special ME course are asked how long they have worked for the current employer, 20-30% of them form a correct phrase: *I have worked for XY for XY years*. The others inevitably make errors (**I work for XY for XY years* / *I am working for XY for XY years*). They admit that this "problem with English presents" sometimes cause them troubles. When they say that, for instance, "they are working for XY", their interlocutors (agents, job interviewers, friends etc.) get the message that their job is just a temporary engagement, because the progressive Present Continuous implies so. Even worse, a wrong decision can be made due to improper usage of Present Perfect Simple and Present Perfect Continuous: *They have repaired the rudder* means the ship can leave port, while *They have been repairing the rudder* means the ship is not ready to leave port. Failure to master some rules in students' previous schooling combined with MTI result in deeply embedded or fossilised errors (Bolinger 1975, p. 682). The mid-term and final tests show that these errors are mitigated, but it is very likely that the rules will be forgotten soon, once the ME course is over.

The fossilised errors appear across all grammar areas, presenting a tough challenge for the teachers. When the rules are clear and consistent, they should be explained properly and clearly. Diversified, targeted and frequent exercises are necessary to excavate fossils and minimise errors.

3.2.3. Articles

The article ("a," "an," "the") plays a significant role in giving the language factuality and accuracy, which could lead to the formation of the category of certainty/indefiniteness (Aarts, 2011). The rules for using "a / an" and "the" depend on many factors including countability, specificity, and pronunciation, which can be hard to predict. Croatian does not use articles so students often omit them or use them incorrectly, for example: **Titanic* instead of *the Titanic*; **Mediterranean Sea* instead of *the Mediterranean Sea*; **Generator is on fire* instead of *The generator is on fire* (if there is only one generator) or *The port / starboard / No. 3 / No. 7 generator is on fire* (if there are more generators on board); **car carriers have few decks* instead of *car carriers have a few decks*. Some of these errors can significantly affect the meaning: "*few decks*" means "*not many*", implying scarcity or a negative sense (not enough), while "*a few*" means "*some*", "*several*", suggesting a sufficient or positive number. As for the generator on fire, the accuracy of information – often including the definite article "the" – is essential for making a decision. Omitting the definite article is probably one of the most common errors of the students attending Maritime English (ME) courses at the Faculty of Maritime Studies in Split.

All ME course are in line and integrated with the Standard Marine Communication Phrases (SMCP). Since SMCP frequently omit articles (e.g. *I have doctor on board*), it is possible that some learner errors result not only from Croatian interference but also from exposure to simplified maritime communication structures.

3.2.4. Prepositions

Croatian language uses a complex case system (Nominative, Genitive, Dative, Accusative, Vocative, Locative, Instrumental) where nouns, pronouns, and adjectives change their endings to indicate roles (subject, object, possession, etc.) (Barić & al, 2026). English retains remnants of cases in pronouns (I/me, he/him…), but the main load on the expression of case relations in English relies on syntax (Halahan et al, 2022). Most of the meanings conveyed by Croatian case forms are transferred into English with the help of word order and

combinations of a noun with prepositions. Prepositions in Croatian do not always correspond directly to English ones, causing confusion and misuse. Here are some of the common MTI errors that Croatians, including the students at the Faculty of Maritime Studies in Split, make when using English: **say it on English* (correct: *say it in English*), **angry at you* / **angry on you* (correct: *angry with you*), **I will meet you on work* (correct: *I will meet you at work*). There are many other common mistakes in idiomatic expressions, due to the different ways these phrases are constructed in Croatian and English, e.g. “in two days” vs. “for two days”: *I am coming to Split in two days for two weeks* means I am arriving the day after tomorrow and staying 14 days in Split; *I am coming to Split for two days in two weeks* means I am arriving in 14 days and will make a short visit. Students of ME, as a type of English for Specific Purposes (ESP) at the Faculty of Maritime Studies in Split, often make these errors. Indeed, some errors may be benign and funny, because a ship’s main engine is typically *at* the stern, not *on* the stern, but other errors may lead to misunderstanding and jeopardise safety on board or in/at shore-based facilities.

3.3. Vocabulary

Most of the mistakes related to vocabulary result from the negative mother tongue interference (MTI), specifically from the words that look similar in Croatian and English but have different meanings (the so-called "false friends"). Earlier in the study, it has been emphasised that the word-by-word translation may lead to errors and confusion. A direct translation from Croatian would make *red wine* **black wine* (*crno vino*) and *blonde hair* **blue hair* (*plava kosa*) (Bradbury, 2023). The list of possible MTI pitfalls is endless and some of them might be very confusing and dangerous in the world of maritime affairs: the examples include *eventually* and *eventualno* (possibly, maybe), *reclaim* and *reklamirati* (advertise or making a claim/complaint about a product/service), *provision* and *provizija* (commission fee), among many others (see: Lewis, 2020). Due to MTI, students often confuse *learn* with *teach*, *borrow* with *lend* or *billion* with *trillion* (OALD, *passim*). The Croatian word *bilijun* means "one thousand billions, i.e. a trillion", whereas the English word *billion* means "one thousand millions". The proper translation of Croatian *bilijun* into English is *trillion*. As Lewis (2020) points out, “we can safely argue that neglecting such difference would amount to significant costs, both semantically and financially.” The Croatian chemical term *silikon* and the English term *silicon* are false friends too. Croatian *silikon* means a polymer compound, whereas English *silicon* is a chemical element (Si). The right translation of *silikon* into English is *silicone*, and *silicon* should be translated into Croatian as *silicij* (Si).

Croatian verb "imati" represents a special case. The basic meaning is "to have, to own". Idiomatic expression, very frequent in everyday use, means "there is / are". In everyday speech, the question "*Šta ima*?" could be translated as "*What’s up*?" or "*What’s going on*?" As a result, due to MTI, students often use the verb "have" incorrectly. Instead of "**I have 21 years*" one should say "*I am 21* (*years old*)". Instead of "**In the cylinder head we have the rocker arm, valves…*", the phrase should be rearranged to sound "more English", for example "*The cylinder head contains / features the rocker arm, valves…*" or "*There are… in the cylinder head*".

In the area of morphology there are few problems (Croatian: "*ima manje problema*"). However, there is one mistake that appears everywhere and all the time: **automatisation* (direct translation of Croatian *automatizacija*) instead of *automation*.

In standard English, nouns referring to inanimate objects like *boat*, *ship*, *train, car, computer, machine* or *country* are supposed to be replaced, when needed, by the pronoun "it" (OALD, *passim*). However, in traditional or informal discourse, using "she" for ships is a deeply ingrained, centuries-old maritime tradition. For example: *The new cruise ship has been commissioned. She will carry 7000 passengers. Her draught is 15 meters*. This practice is sometimes extended to countries (when the concept of motherhood is attached), to other large and powerful vehicles like trains, even to machines and computers, especially by people who work with them closely or own them proudly (e.g. *She's a beauty!*). While less common, some individuals, often women, might refer to their cars or other machines with male names and use the pronoun "he". Consequently, Croatian students may be encouraged to use "he" or "she" for inanimate objects, especially due to the fact that all Croatian nouns (feminine, masculine or neutral) are replaced by pronouns according to their gender (she, he, it), and this sometimes results in incorrect usage of English pronouns. In Croatian, for instance, the ship is a masculine noun (*brod*) and, in line with MTI, students often use "he / his" instead of "she / her" or "it / its".

Finally, English easily make compound noun phrases, e.g. “two-stroke slow-speed marine turbocharged ported engine”, which should be carefully translated, rearranging the word order when necessary. Literal translation from Croatian often leads to awkward or incorrect phrases, which may result in misunderstanding

and confusion, which again may jeopardise the safety of maritime operations, human life and marine environment.

Teachers should be aware of students' background and they should know that some errors may stem from students' first language (L1). Kazazoğlu states that teachers as facilitators should be tolerant and patient in students' language learning process. "Being aware of students' L1 interference errors, teachers can design the lessons more in line with their students' needs. By having a needs analysis, teachers can adapt their lesson plans, materials, and activities to diminish L1 errors" (Kazazoğlu, 2020). AbdAlgane points out that explicit instruction, cultural context, background information, authentic language use, multimedia resources, and a practice context can improve learners' English idiomatic expressions and reduce mother tongue interference (AbdAlgane, 2025).

4. Conclusion

This study has identified, analysed and categorised typical mother tongue interference (MTI) errors made by Croatian students attending Maritime English (ME) classes at the Faculty of Maritime Studies in Split. The errors have been identified in all key language areas, particularly in a) pronunciation, spelling and capitalisation; b) syntax (incorrect use of the word order, tenses, articles, prepositions, pronouns and plural forms); and c) vocabulary (literal translation, false friends and idiomatic expressions). The influence of the Croatian grammatical and lexical framework may affect the proficiency in ME, as a type of English for Specific Purposes (ESP). The problem may affect the communication, safety of navigation, efficiency and daily operations in various areas of the maritime industry.

Recognising these frequent MTI mistakes helps educators to tailor their teaching methods effectively. Addressing the MTI errors through targeted teaching strategies can significantly improve Croatian students' accuracy and confidence in English communication. These strategies can include focused (targeted) practice, contrastive analysis between Croatian and English syntax, clear explanations, contextualized teaching, phonetic training, corrective feedback, and soft approach tools aimed at encouraging self-correction, boosting students' confidence, improving their performance, and mitigating the problem.

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Exploring Technostress and Seafarer Wellbeing: Survey Insights and Mitigation Strategies

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Abstract: The maritime industry is rapidly digitalising, requiring seafarers and shore-based professionals to continually update their skills in complex technologies. This constant need to learn and adapt contributes to technostress, defined as psychological strain arising from difficulties in coping with information and communication technologies. Although technostress remains understudied in maritime settings, it poses a critical threat to seafarer wellbeing, with perceived impacts on mental health and work performance. This paper applies the Transactional Model of Stress and Coping, examines technostress causes, prevention, and maritime-specific factors, and identifies gaps like resistance to change and mental health impacts in the digitalised shipping environment. The main contribution of this study is a detailed survey of current and former seafarers of various maritime ranks and ship types. The study uses a questionnaire with Likert-scale to assess technostress and its effects on seafarers and their work. Survey results from 70 current and former seafarers show mean technostress indicator scores near the midpoint of the five-point scale, with techno-uncertainty and techno-overload rated highest. Beyond analysis, this study proposes solutions in the form of digital training simulations for maritime environments, user-friendly interfaces on emerging technologies, and intervention by regulatory bodies such as the IMO to set proper policies regarding the mental health of seafarers.

Keywords: Technostress; Seafarer wellbeing; Maritime digitalisation; Exploratory survey; Human-centred design; IMO policy.

1. Introduction

Seafarers operate increasingly digitalised vessels under chronic fatigue, contractual uncertainty, and limited shoreside support. ECDIS, AIS, integrated bridge systems, dynamic positioning, and a steady accumulation of compliance software demand sustained attention alongside safety-critical watchkeeping. DNV (2023) reports that more than 80% of seafarers feel inadequately trained for emerging technologies. The psychological cost of this transition namely technostress, has received less empirical attention than its operational benefits, and existing maritime-specific evidence remains thin.

This study addresses that gap exploratorily. We surveyed 70 active and former seafarers across deck and engine ranks using single indicator items adapted from the Technostress Creators Inventory (Tarafdar et al., 2011), and analysed verbatim free-text responses thematically. The objectives were narrower than the framework's original psychometric scope: to map indicator-level patterns of digital strain in a maritime sample, document the most frequently cited stressors and suggested mitigations in respondents' own words, and identify directions for fuller measurement and intervention research. The paper does not test formal hypotheses. It presents descriptive evidence, situates that evidence in the existing literature, and proposes directions worth exploring including a working prototype that operationalises the most consistently identified intervention area.

2. Background and Theoretical Framework

The Transactional Model of Stress and Coping (Lazarus and Folkman, 1984) conceptualises stress as a dynamic interaction between perceived demands and perceived coping resources. Within this frame, seafarers conduct a primary appraisal of digital systems (threat versus challenge) followed by a secondary appraisal of whether available training, support, and rest are sufficient to manage these demands. Technostress arises when digital demands are appraised as exceeding available resources. This perspective is useful because it shifts attention away from technology per se toward appraisal–resource imbalance and directs intervention design toward training, support, and rest, while accommodating maritime amplifiers such as isolation, hierarchy, and contractual uncertainty as constraints on the resource side.

Tarafdar et al. (2011) describe technostress along five dimensions that are all relevant at sea: techno-overload (digital systems multiplying workload), techno-complexity (difficult, heterogeneous interfaces), techno-uncertainty (frequent changes and updates), techno-invasion (work–rest boundary erosion via constant connectivity), and techno-insecurity (concern about job loss to automation). These strains are moderated by factors such as targeted onboard training (DNV, 2023), chronic fatigue from watchkeeping documented in Project HORIZON and MARTHA, and human-factors issues like alarm fatigue and alarm management. Bridge Resource Management provides a template for scenario-based training that integrates technical and non-technical skills under operational pressure.

The maritime technostress evidence base remains limited. Existing studies often rely on general occupational health instruments rather than technostress-specific measures, and rank-level patterns are under-described, while IMO and STCW frameworks emphasise digital competence but not mental health. Against this backdrop, the present study adopts a descriptive approach intended to map indicator-level patterns of digital strain, capture seafarers' own accounts of stressors and mitigations, and inform the design of future multi-item, longitudinal work.

3. Methodology

3.1. Design and Instrument

We conducted a quantitative, cross-sectional online survey using Google Forms with four sections. Section 1 captured demographics: rank, department, years of sea service, vessel type, and age group. Section 2 included five Likert items (1 = Strongly Disagree, 5 = Strongly Agree) on work-induced stress: fatigue and sleep loss from watchkeeping, administrative workload eroding rest, social isolation during contracts, contract length and sign-off uncertainty, and perceived superior support for mental health. Four items functioned as burden indicators (higher scores = greater strain) and superior support as a resource indicator (higher scores = greater support). Section 3 comprised six Likert items adapted from the Technostress Creators Inventory (Tarafdar et al., 2011): one item for each technostress dimension (techno-overload, techno-complexity, techno-invasion, techno-uncertainty, techno-insecurity) plus a resource item on training adequacy ("I receive adequate training before joining the vessel on the specific technologies I am expected to use"). Section 4 contained two open-ended questions on the biggest current stressor and suggestions for managing new technology. Each technostress dimension was measured with a single indicator item rather than a multi-item subscale to keep the survey feasible for seafarers under contract conditions. This brevity has direct consequences for measurement quality, which we address in Section 5.

3.2. Recruitment and Sample

Participants were recruited through purposive convenience sampling using maritime professional networks. Seventy valid responses were received. Recruitment ran from 01/03/2026 to 30/04/2026. Respondents provided informed consent before completing the survey. The form collected email addresses for response validation only; these were not analysed and have been removed from the working dataset. Respondents were informed that responses would be reported in aggregate form only.

3.3. Qualitative Data Coding

Forty-five respondents (64.3%) provided a free-text response to the stressor item; forty-six (65.7%) responded to the suggestions item. Three responses to the stressor item and thirteen responses to the suggestions item were judged non-substantive (single characters, "no", "yes", or unintelligible strings) and were excluded from theme counts. Thematic analysis of the remaining responses followed an inductive approach: themes were

derived from the data rather than imposed from a pre-existing frame. Responses that addressed more than one theme were assigned to multiple categories. Verbatim quotes presented in Section 4.6 have been lightly edited for spelling only; original wording is preserved.

3.4. Analysis

For each Likert item, we computed means and standard deviations. The five technostress indicators were retained as separate single-item measures rather than combined into an aggregate, since each taps a conceptually distinct dimension (Tarafdar et al., 2011) rather than a common underlying construct. We computed Pearson correlations between each technostress indicator and each wellbeing burden item (with 95% confidence interval, p-value, and N), and between each resource item and the technostress indicators, to probe the Transactional Model's demand–resource framing. Mean technostress scores by experience band, age group, and vessel type are reported descriptively with cell sizes; no inferential tests were conducted for subgroup differences due to small cells, and these patterns are treated as hypothesis-generating only. Free-text vessel-type entries containing spelling variants of "dredger" were collapsed into a single category for analysis. All analyses were conducted in Python 3.12 using the pandas and SciPy libraries.

4. Results

4.1. Sample Profile

Of the 70 valid responses, 41 (58.6%) came from the engine department, 26 (37.1%) from the deck department, and 3 (4.3%) from other roles. The most common ranks were 3rd/4th Engineer (n = 22, 31.4%), 2nd/3rd Officer (n = 19, 27.1%), Chief Engineer (n = 7, 10.0%), 2nd Engineer (n = 7, 10.0%), Chief Officer/Mate (n = 4, 5.7%), and Master/Captain (n = 3, 4.3%); the remaining 11.5% were spread across ETO, ratings, and write-in categories. Sea experience was distributed across 1–5 years (n = 24, 34.3%), 11–20 years (n = 23, 32.9%), 6–10 years (n = 12, 17.1%), more than 20 years (n = 10, 14.3%), and under one year (n = 1,1.4%). Age was concentrated at 26–35 (n = 33, 47.1%) and 36–45 (n = 18, 25.7%); smaller groups at 18–25 and 46–55 (n = 8, 11.4% each), and 55+ (n = 3, 4.3%). Vessel types (after collapsing dredger spelling variants) were Dredger (n = 23, 32.9%), Tanker (n = 17, 24.3%), Offshore/DP Vessel (n = 15, 21.4%), Container Ship (n= 8, 11.4%), Bulk Carrier (n = 6, 8.6%), and other (n = 1, 1.4%). The dredger and offshore/DP concentration reflects the recruitment network and is unlikely to be representative of the global fleet.

4.2. Wellbeing Indicators

Item	M	SD
Fatigue / sleep loss from watchkeeping	3.16	1.24
Administrative workload eroding rest	2.89	1.20
Social isolation during contract	3.23	1.21
Contract length / sign-off stress	2.96	1.32
Superior support for mental health (resource)	3.61	1.20

Table 1. Wellbeing item descriptives (N = 70).

Burden items clustered close to the scale midpoint, with social isolation (M = 3.23) and fatigue (M = 3.16) the highest. Perceived superior support, reported as a resource indicator rather than a stressor, was at M = 3.61, indicating a moderate perceived level of onboard support.

4.3. Technostress Indicator Items

Table 2 reports the technostress-section descriptives.

Indicator (Dimension)	M	SD
Forced to work faster (Techno-overload)	3.09	1.24

Equipment/software too complex (Techno-complexity)	2.79	1.18
Cannot disconnect (Techno-invasion)	3.03	1.31
Constant changes/updates (Techno-uncertainty)	3.10	1.25
Worry about automation (Techno-insecurity)	2.87	1.38
Training adequacy (resource, N = 46)	3.57	1.33

Table 2. Technostress indicator descriptives (N = 70 unless noted).

All five technostress indicators sat just below or around the midpoint of the five-point scale (M = 2.79 to 3.10). Techno-uncertainty (M = 3.10) and techno-overload (M = 3.09) were the highest, techno-complexity (M= 2.79) the lowest. The spread across dimensions was narrow (range = 0.31 scale points). Training adequacy, reported separately as a resource item, was M = 3.57 (n = 46).

These are single-item indicators and should not be read as validated dimension scores. The pattern is consistent with prior maritime work suggesting that workload intensification and the constant-change pressure are leading features of digital strain at sea, but the differences between dimensions in this sample are too small to support strong claims about which dimension dominates. Figure 1 illustrates the mean scores standard deviations for each technostress dimension.

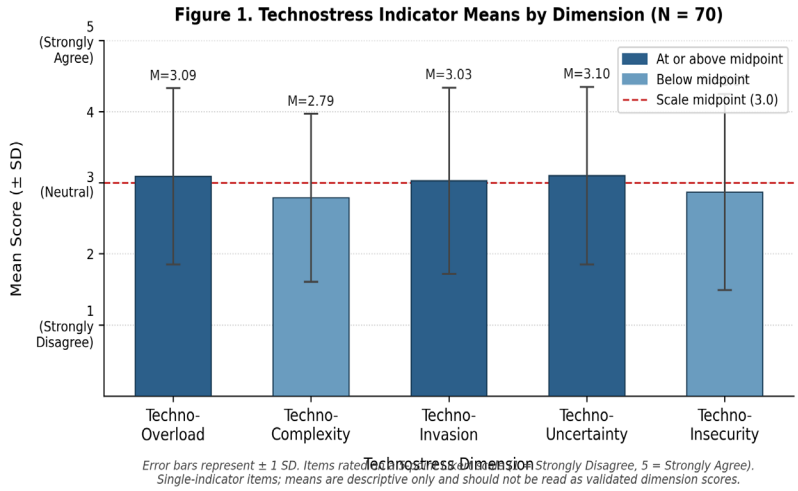


Figure 1. Technostress indicator means by dimension (N = 70). Error bars represent ± 1 SD.

4.4. Variation by Experience, Age and Vessel Type

The pattern is non-monotonic. Respondents with more than 20 years at sea showed the highest mean technostress score across indicators (M = 3.76, n = 10), and the 11–20 year cohort the lowest (M = 2.53, n = 23). With n = 10 in the highest-experience cell, no inferential weight should be placed on this. If the pattern replicated in a larger sample, it would challenge the intuition that experience confers digital resilience. The age pattern echoes the experience pattern: respondents aged 55+ (n = 3) showed substantially higher mean technostress than younger groups, although n = 3 makes this a descriptive observation only.

Container ships showed the highest descriptive mean (M = 3.48, n = 8), followed by dredgers (M = 3.16, n = 23). The pattern is broadly consistent with the expectation that vessel types operating in high-tempo, technologically dense environments generate greater digital strain, but small cells and likely sampling-frame effects make this provisional.

4.5. Qualitative Findings

Forty-five respondents provided substantive stressor descriptions and thirty-three offered suggestions. The clearest stressor theme was sleep loss tied to 6-on/6-off watch patterns: “Not getting continuous long sleep hours since duty time is 6 on and 6 off” and “my watch is 6 on 6 off so I don’t have proper sleep, that makes me more stressed.”

Port-call and inspection compression emerged as a structurally maritime form of techno-overload, with one engineer describing "HFO bunker, LSMGO bunker, sludge discharge, spares, provisions, technicians, and sign on/sign off… all happening within 20 hours" on a 6-on/6-off schedule, alongside "continuous inspections of vessels and less shore leaves." Training inadequacy appeared both as a stressor and the dominant mitigation, captured in calls to "provide proper training before introducing new technology… and offer continuous technical support so crew can work confidently without added stress," with respondents emphasising pre-joining simulation and competent instructors outside working hours.

Onboard hierarchy and senior behaviour ("all depends on our top rank attitude"; "seniors asking irrelevant questions to juniors") were identified as additional amplifiers of technostress, consistent with wider maritime culture literature. Read together, these verbatim accounts add maritime-specific texture to the quantitative pattern, pointing to watch schedules, port-call compression, pre-joining training, and hierarchy as core drivers of digital strain that single indicator items do not surface directly.

4.6. Core Inferences

Four descriptive inferences follow from the data. First, technostress indicator means in this sample sit close to the scale midpoint rather than in a high-stress range. The strain reported is real but not acute; this is a window in which targeted intervention may avert escalation rather than respond to crisis. Second, three of the five technostress dimensions correlated robustly with wellbeing burden: techno-overload, techno-invasion, and techno-uncertainty. Techno-complexity did not. This suggests that the pace, pervasiveness, and unpredictability of digital demand are the principal candidates for intervention, while interface difficulty per se is a weaker driver in this sample. Third, the resource items (superior support, training adequacy) showed essentially no consistent correlation with the individual technostress indicators. This is contrary to the Transactional Model's prediction; we discuss possible interpretations in Section 5. Fourth, the qualitative material identifies a cluster of structurally maritime stressors that do not appear cleanly in the indicator items: 6-on/6-off watch patterns, port-call and inspection compression, pre-joining training inadequacy, and onboard hierarchy. Respondents do not describe themselves as unable to use digital systems; they describe being expected to use them under conditions that do not include adequate familiarisation, support, or rest. The training-technology gap is the most consistent finding: better training was the most frequent suggested mitigation by a clear margin.

5. Discussion

Several limitations bound the strength of inference. First, the small, convenience sample (N = 70) limits statistical power and generalisability, and subgroup cells (e.g. >20 years' experience, n = 10; 55+ age, n = 3) are too small to support inference. Second, each technostress dimension is measured with a single item, precluding internal consistency assessment at the dimension level and reducing reliability. Indicator means should be read as descriptive signals rather than validated dimension scores in the sense of Tarafdar et al. (2011). Third, common method bias is likely, as all items were self-report Likert responses completed in a single sitting, inflating correlations between indices to an unknown degree (Podsakoff et al., 2003), and self-report is additionally subject to social desirability and recall bias. Fourth, the cross-sectional design prevents any inference about causal direction between technostress and wellbeing strain. Fifth, the sampling frame (maritime professional networks) likely over-represents digitally engaged seafarers and particular vessel types (tankers, dredgers, offshore/DP vessels together ≈79% of the sample). Sixth, missing data on the training adequacy item (24 missing; N = 46 valid) constrains the precision of estimates involving this resource indicator. These limitations frame all subsequent claims.

The descriptive pattern is partially consistent with the Transactional Model. The per-dimension pattern — overload, invasion, and uncertainty significantly correlated with wellbeing burden — points to demand-side amplifiers anticipated by maritime context theory. More striking is the null association between the resource items and the technostress indicators: if the Transactional Model held straightforwardly here, higher perceived support and training would track lower technostress, which these data do not show. This may reflect methodological noise in single-item, non-technology-specific resource measures, a substantive "saturation" effect in which support and training sit below a protective threshold, or sample-specific artefact; in any case, the result highlights multi-item, technology-specific resource measurement as a priority for follow-up work.

Qualitative findings add a distinct maritime texture to this pattern. The 6-on/6-off watch and port-call compression themes describe stressors that shore-based technostress research rarely surfaces but which align

with the broader maritime fatigue evidence, while the hierarchy theme (“depends on our top rank attitude”) points to organisational-cultural amplifiers not captured by Tarafdar’s framework yet consistent with maritime culture literature; maritime adaptations of technostress models should therefore treat hierarchy and onboard culture as explicit moderators. Descriptive subgroup patterns by experience and age suggest, but cannot test, a non-linear relationship in which highly experienced and older seafarers report higher technostress than mid-career colleagues, a hypothesis that warrants examination in larger, stratified samples with implications for familiarisation design across career stages.

Single-item measurement is the central limitation on inference. Indicator means should not be treated as validated dimension score. Future research should prioritise multi-item measurement using adapted Tarafdar and Ragu-Nathan item sets with formal psychometric validation, and longitudinal designs that track within-respondent change across contracts to separate chronic from transient strain.

6. Directions Worth Exploring

The directions below are framed as candidates for further investigation rather than evidence-based prescriptions. Each is tied either to a specific finding from this sample or to prior literature.

6.1. Training and Development

Better training was the single most frequently suggested mitigation (n = 14 of 33 substantive suggestions, 42%). The qualitative material is specific: respondents called for "proper simulation before joining," for training "before new technology comes," and for instructors who are competent and timed outside working hours. This points toward vessel-specific, simulator-based digital familiarisation as a research-supported intervention area. The Bridge Resource Management literature (Hetherington, Flin and Mearns, 2006) provides an existing template for scenario-based training that integrates technical and non-technical skills under operational pressure. Practical extensions worth piloting include structured digital familiarisation periods at the start of a tour, multi-alarm prioritisation simulations, and explicit modules on recognising and managing cognitive overload — consistent with the Transactional Model's framing of shifting appraisal from threat to challenge (Lazarus and Folkman, 1984).

6.2. Organisational Support

The techno-invasion finding (M = 3.03) and the qualitative protect-rest-hours and don't-reduce-manpower themes point toward dedicated onboard and shoreside technical support, alongside tech-free rest protocols, as candidate interventions. The senior-behaviour theme adds a cultural dimension: technical support is partly a matter of culture, not merely staffing. One respondent's suggestion of "compulsory video calls with management with officers and ratings monthly, monthly feedback from all ship members without name" is a concrete, testable proposal.

6.3. System Design

The techno-complexity null finding is informative. In this sample, interface difficulty per se did not correlate significantly with wellbeing burden, while overload, invasion, and uncertainty all did. Design efforts focused narrowly on usability may therefore be necessary but not sufficient. The user-friendly/simpler-systems theme in the suggestions table (n = 2) is small but consistent with prior human-factors evidence on alarm management and interface heterogeneity (Gao et al., 2025; Hetherington, Flin and Mearns, 2006). Standardised alarm prioritisation, consistent interaction patterns across vendors, and procurement requirements for usability testing with serving seafarers are directions worth exploring.

6.4. Policy

The indicator-level and qualitative patterns together raise questions for IMO and STCW frameworks, which currently mandate digital competency without corresponding mental health provisions. Whether technostress should be formally recognised as an occupational health risk under MLC 2006, and whether mandatory rest provisions should explicitly address non-emergency digital alerts, are questions the present data do not answer but do motivate. The qualitative 'reduce paperwork' theme (n = 4 in suggestions) and the wider maritime literature on administrative burden suggest that compliance documentation reform may have more

impact on digital strain than further digital tooling. Larger, longitudinal studies are needed before specific policy proposals can be made with confidence.

6.5. Prototype Implementation: "ShipMind"

To operationalise the training-and-support directions outlined in §6.1–6.2, three of the authors developed ShipMind, an Android prototype that provides offline reference content and structured troubleshooting flows for shipboard systems such as ECDIS, AIS, VDR, GMDSS, and engine automation. The core design principle, drawn from the qualitative findings, is to lower the cost of in-context help-seeking by making role-specific, plain-language reference material available without internet access at the moment of use.

Three design choices reflect this principle: content is filtered by rank so that different roles see different recommended topics; each topic is structured into three depth levels (overview, technical breakdown and an "on watch" checklist) to support both pre-joining familiarisation and on-console reference; and all content is served via a versioned JSON system that allows updates without rebuilding the application package. The prototype is currently at MVP stage; no user evaluation has yet been conducted, so its impact on technostress remains to be tested. We present it here as a concrete instantiation of a promising design direction rather than a validated intervention, with materials archived at this repository (release v0.1.0).

7. Conclusion

This exploratory cross-sectional survey of 70 seafarers found that technostress indicator means sat close to the midpoint of the five-point scale, with techno-uncertainty (M = 3.10) and techno-overload (M = 3.09) the highest-rated dimensions. Three of the five technostress dimensions — overload, invasion, and uncertainty — correlated robustly with wellbeing burden; techno-complexity did not. The most consistent qualitative theme was a training-technology gap: better training was the most frequent suggested mitigation, and pre-joining training inadequacy appeared as a stressor theme. The findings are descriptive and hypothesis-generating; the small sample, single-item measurement, modest reliability, and convenience sampling preclude stronger inference. This study's maritime contribution lies in identifying structurally maritime stressors that existing frameworks do not surface directly. The 6-on/6-off watch pattern, the port-call and inspection compression theme, and the onboard hierarchy theme emerged in respondents' own words as distinctive drivers of digital strain at sea. These findings are the most useful for designing future maritime-specific technostress research. This study is intended to motivate future research rather than substitute for it, and to begin documenting, in seafarers' own words, what digital transformation feels like at sea.

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A framework for evaluating STCW refresher training effectiveness and seafarer recovery

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Abstract: The STCW Convention mandates refresher training to ensure seafarers' continued competence in safety-critical skills. In parallel, shipping companies increasingly require additional non-STCW internal training, often delivered through digital platforms. While these developments aim to strengthen compliance and safety, concerns are growing that training obligations, particularly when scheduled during shore leave, may affect recovery, increase fatigue, negatively affect quality of life and increase financial burden. Despite the regulatory importance of these challenges, systematic evidence capturing both training effectiveness and welfare impacts remains limited. This paper presents the development of a structured, questionnaire-based research framework designed to evaluate the effectiveness of STCW refresher training alongside the impact of STCW and non-STCW training demands on seafarers' shore-leave recovery. The research idea is grounded in competence-based training principles delivered by the International Maritime Organization (IMO) on fatigue guidance and welfare expectations reflected in the Maritime Labour Convention (MLC). It captures training exposure, delivery mode, training governance quality, early re-contracting pressure, psychological detachment during leave, perceived recovery, and safety- and retention-related outcomes. The proposed framework enables analysis of key interactions between competence assurance, recovery protection and relevance of the non-STCW training, including the conditions under which digital and hybrid training models may mitigate or aggravate fatigue. By explicitly linking training delivery and governance practices, the study addresses a critical gap between regulatory intent and seafarer experience. This paper contributes to enhancing the policy evaluation framework in supporting maritime administrations, training providers, and shipping companies in developing training systems that maintain safety standards while safeguarding seafarer wellbeing.

Keywords: STCW refresher training; seafarer fatigue; shore leave recovery; online/hybrid training; maritime policy

1. Introduction

Considering the fact that shipping is a cornerstone of global trade, carrying around 80% of its volume (UNCTAD, 2025), at the center of industries mechanism are seafarers, recognized as key workers for their contribution in maintaining the global supply chain and movement of goods (ILO, 2025). Their essence is particularly important during the periods of global disruptions, crises, and instabilities, caused by natural and anthropogenic impacts, for instance, geopolitical issues, epidemiological crises, or climate change effects (Notteboom et al., 2026). Currently, there are approximately around 1,9 million seafarers worldwide (UNCTAD, 2021), so the ultimate objective is to structure the effective legal framework to enhance the protection of seafarers' rights, address the recent issues, but also incorporate the human element parameters, including the influence of human behavior, welfare, and working conditions on maritime safety and operations. This is particularly relevant in the complex maritime environment, where the multinational nature of shipping and unbalanced standardized practices may create legal uncertainties that can jeopardize the status and legal rights of seafarers. It includes various stakeholders as shipowners, flag states, labor market and nations, and port states (Sampson, 2013), forming an institutionalized labyrinth of differentiated rules, standards, and norms, which causes significant challenges for the crew on board. Due to the universal business characteristics of shipping, the International Maritime Organization (IMO) has created a set of uniform, mandatory standards for training and certification of all personnel on board ships by adopting the International Convention on Standards of

Training, Certification and Watchkeeping for Seafarers (STCW) (IMO, 1978). To maintain the certification validity, the STCW Convention requires the demonstration of continued competence in safety-critical functions through refresher training or equivalent evidence of competence at defined intervals (IMO, 2017). Additionally, there is a growing requirement for shipping companies to attend the short non-STCW courses, which are tailor-made and adjusted to different types of vessels and company needs (Gundić et al., 2024). These two-fold approaches are a key mechanism in maintaining the effective and consistent seafarers' education and training, while simultaneously enhancing compliance and safety. It is important to emphasize that maritime training has evolved from conventional physical instruction modes towards digital learning (Tagouzi, 2024), with the current practice favoring hybrid models that combine online theory with physical assessment. However, literature consistently shows that e-learning cannot fully replace hands-on training for safety-critical skills, making integrated approaches essential for the assurance of effective competence (Galić et al., 2020). However, besides the requirement of continued competence of seafarers' standards to be maintained over the course of their professional careers, along with the increasing requirement of taking the short courses based on the company's needs, there is a rising concern about the impact of the incremental training obligations on the quality of the seafarer recovery during the shore leave period. This argument is associated with the empirical studies, which highlighted the critical role of adequate leave in mitigating fatigue (An et al., 2022), but also the strong link between seafaring fatigue and workload, work demands, and insufficient recovery periods (Smith et al., 2006; Oldenburg et al., 2010). Generally, fatigue is recognized as a significant contributor to maritime accidents and reduced performance (Rajapakse et al., 2023; IMO, 2019), so these pressures, combined with organizational and economic demands, may also impose additional burdens on seafarers, raising important concerns for both safety and workforce sustainability. Based on the potential harmful effects and risks to seafarers caused by fatigue, the IMO has adopted fatigue guidance in 2019, treating this hazard as a system-level safety risk driven by organizational factors (IMO, 2019). Simultaneously, the Maritime Labour Convention (MLC) on welfare aspects establishes minimum global standards for seafarer wellbeing, including the right to rest and leave, protection of health and wellbeing, work-life balance and dignity, and economic protection (ILO, 2006).

Concerning the regulatory importance of these challenges and the limited empirical evidence of holistic evaluation of seafarer training effectiveness and welfare impacts, this paper aims to develop a research framework by examining, defining, and aggregating the main research elements forming the analytical model. This is done by conducting a systematic analysis of mandatory or internal training practices and their implications on the seafarer recovery phase, which is used to design the three-fold logical layer of the research, including the inputs, mechanisms, and outcomes. These variables collectively capture the relationship between training demands, their impact on seafarers' recovery and fatigue, and the resulting implications for safety, well-being, and workforce sustainability. Additionally, the research logic allows for measuring cause, mechanism, and effects of the determined research problem, providing a structure and a foundation that is to be used for the development of a highly robust questionnaire for conducting a practical investigation among seafarers. The methodological concept of the model enables addressing how the intention to retain and secure competence requirements correlates to recovery protection, while also associating the effectiveness of hybrid training models in affecting the safety-fatigue relation. This study contributes as a foundation in designing the policy-relevant evaluation tool by defining the key variables and research areas that can support maritime administrations, training providers, and shipping companies to improve the training ecosystem by balancing the potentially conflicting fragments of keeping the highly committed role in maintaining the safety standards while safeguarding seafarer wellbeing.

2. Regulatory and conceptual background

The methodological aspect of this research is grounded within the interaction of three structural elements: STCW and MLC Conventions and IMO guidelines on seafarer fatigue challenges. As already indicated, the STCW Convention has been established as a universal regulatory framework for maritime education and training (MET) since 1978 (Karahalil et al., 2025), defining the expected competence standards, the necessary level of knowledge, understanding, and required proficiency, while emphasizing the methods and criteria for evaluation of demonstrating these competencies. This indicates the strong commitment to ensuring an effective competence-based training and satisfying the requirements of specific practical and performance-based results (Manuel, 2017). It can be concluded that the STCW is primarily a safety-focused convention (Masodzadeh et al., 2024), with the primary objective of securing safe ship operations. In order to demonstrate continued

competence in safety-critical functions throughout their careers, requirements regarding the refreshment training for certain competences or equivalent evidence of competence at regular intervals were introduced (IMO, 2011). The purpose of introducing refresher requirements was to preserve necessary life-saving skills beyond compliance, strengthening training as a key mechanism for maintaining operational safety and compliance within the maritime industry. Despite the primary objectives of introducing refresher training for a certain category of seafarers, questions have been raised about its justification, especially in terms of imposing additional financial burden and questionable competencies of trainers and instructors (Belev et al., 2018), but also the shortage of qualified trainees (Joo et al., 2025). Also, there is a growing demand from shipping companies to seafarers to attend numerous non-STCW training courses (Lušić et al., 2019), a system which is more versatile and adaptive to the current trends and demands in the industry, opposed to IMO Model Courses, which change more slowly. At the same time, fatigue is being recognized as a major safety concern in shipping, despite being highlighted as a highly identifiable and preventable cause of accidents (Bhatia et al., 2025). Beyond having negative implications in terms of safety aspects, fatigue especially affects human performance and decision-making (Ma and Liao, 2025). According to IMO fatigue guidelines, fatigue is not solely an individual condition but a system-level risk influenced by organizational factors such as workload, scheduling practices, and administrative demands (IMO, 2019). This has prompted several authors to question the current design of the shipping industry system, particularly its effectiveness in addressing fatigue and protecting seafarers' well-being. Jepsen et al. (2015) argue that the effectiveness of the current legislative framework, the level of industry compliance, the management of the international merchant fleet, and the adequacy of working, living, and sleeping conditions at sea are due to the widespread occurrence of seafarer fatigue and the severity of its consequences. Also, Rüpke and Athanassiou (2024) emphasize the importance of changing and improving the current regulations and management in terms of working hours, crew sizes, and corresponding workloads, demanding onboard conditions which results from a combination of individual, environmental, and organizational conditions. These principles highlight that operational requirement, including training obligations, may contribute to fatigue if they interfere with adequate rest and recovery. Regardless of providing a critical contribution to the worldwide economy and society, seafarer welfare has not been addressed sufficiently in the maritime industry (Exarchopoulos et al., 2018). This is the reason behind establishing minimum global standards for seafarer welfare, including the right to rest, leave, and protection of physical and mental health, with the introduction of MLC, which was adopted by the ILO (ILO, 2025). The Convention emphasizes the importance of recovery periods, including shore leave, as essential for maintaining well-being and sustaining long-term employability. These provisions position rest not only as a welfare requirement but also as a contributing factor to safe maritime operations. Despite being highlighted as the "seafarers' bill of rights", some authors are questioning its effectiveness. Zhang et al. (2020) argue that although the MLC 2006 significantly improved seafarers' rights, its effectiveness in protecting welfare remains uncertain due to inconsistent implementation across jurisdictions and its inability to fully address all challenges faced by seafarers. Additionally, the research by Fotteler et al. (2018) addresses several similar critical issues that remained uncovered within the MLC, such as long working hours associated with low manning, safety onboard, social difficulties, and food, but also underlines the necessity to undergo assessment of its impact to enable required living and working standards.

This brief overview of the regulatory framework and individual objectives imposed reveals an inherent tension within the maritime governance system, mainly visible in the lack of integrated empirical evidence examining how training requirements interact with fatigue, recovery processes, and seafarer wellbeing. This issue highlights the need for a comprehensive evaluation framework capable of simultaneously assessing training effectiveness and its human-centered implications.

3. Problem definition and conceptual model development

3.1. Gap analysis and research justification

Despite an extensive regulatory framework governing MET and seafarer welfare, existing research has largely addressed these challenges in isolation. Studies on maritime training predominantly focus on competence development, compliance with STCW requirements, and the effectiveness of training delivery methods. On the contrary, research on fatigue has examined the impact of workload, working conditions, and insufficient rest on seafarers' health, safety, and performance. However, limited attention has been given to the interaction between these domains, particularly the extent to which training obligations, especially when

imposed during shore leave, may influence recovery processes and contribute to fatigue. This lack of integration represents a critical gap in both academic research and regulatory evaluation. While STCW compulsory training is designed to enhance safety through competence assurance, it can also impose additional workload that interferes with rest and recovery, thereby affecting seafarers' performance. The problem arises in the fact that the existing framework lacks a structured approach to assess this potential conflict or to evaluate whether current training practices achieve their intended safety outcomes without generating unintended adverse effects on seafarer wellbeing. To address this challenge, the present study develops a conceptual framework that integrates training effectiveness with human-centered outcomes, including recovery, fatigue, and retention. By linking training demands, both those of mandatory STCW and internal non-STCW requirements, with recovery processes and downstream operational impacts, the study provides a basis for evaluating maritime training systems from both a competence and a well-being perspective. This study integrates training effectiveness and fatigue-related recovery within a single analytical framework. Figure 1 presents the conceptual structure of the proposed framework, illustrating the relationships between training inputs, human-centered mechanisms, and operational outcomes.

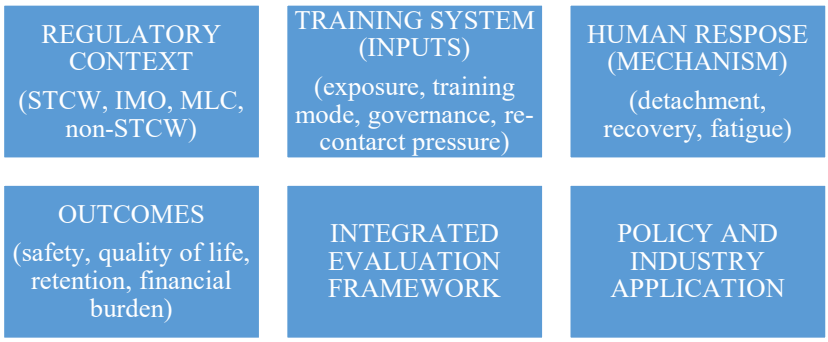


Figure 1. Conceptual framework linking training inputs, human-centered mechanisms, and operational outcomes.

3.2. Model rationale

The increasing complexity of maritime training requirements, combined with increasing concerns regarding seafarer fatigue and well-being, requires an integrated analytical framework capable of capturing both operational and human-centered dimensions of training systems. While existing regulatory instruments emphasize either competence assurance or fatigue mitigation, they do not provide a structured mechanism for evaluating the interaction between these domains. In response, this study proposes a conceptual model that links training demands with human recovery processes and resulting safety and workforce outcomes. The model is grounded in a systems perspective, recognizing that training obligations constitute a form of organizational workload that may influence fatigue, recovery, and performance. By integrating these elements, the framework enables a comprehensive assessment of whether current training practices achieve their intended safety objectives without generating unintended adverse effects on seafarers.

3.3. Structure, relations between components, and contributions of the model

The proposed model is organized into three interrelated components:

1. Inputs related to training,
2. human-centered mechanisms, and
3. operational and workforce outcomes.

Training-related inputs represent the demands imposed on seafarers through regulatory and organizational requirements. These include:

- Training exposure, referring to the volume and intensity of training obligations, including both STCW-mandated refresher courses and internal training imposed by the company (non-STCW);

- Training delivery mode, encompassing physical (onsite), digital (online), and hybrid formats, which differ in their flexibility, accessibility, and potential burden on seafarers;
- Training governance quality, defined as the degree of planning, transparency, scheduling predictability, and avoidance of redundancy in training requirements;
- Early re-contracting pressure, reflecting organizational practices that reduce the effective duration of shore leave and may increase cumulative workload.

Collectively, these factors represent the organizational load associated with training systems. The second component of the model captures the internal human-centered mechanisms through which seafarers respond to training demands, focusing on recovery and processes associated with fatigue. Two key constructs are identified:

- Psychological detachment, referring to the ability of seafarers to mentally disconnect from work demands during shore leave;
- Perceived recovery, defined as the extent to which seafarers feel physically and mentally restored before returning to duty.

These mechanisms are central to fatigue risk management, as insufficient detachment and recovery contribute to cumulative fatigue and reduced performance capacity. The model assumes that training demands, particularly when imposed during shore leave, may interfere with these processes. Finally, the ultimate component of the model addresses the consequences of training and recovery dynamics for both safety and workforce sustainability. These include:

- Safety-related outcomes, such as perceived readiness, confidence in emergencies, and the ability to perform safety-critical tasks;
- Quality of life, encompassing overall well-being, stress levels, and balancing everyday life and work; and
- Retention intentions, reflecting seafarers' willingness to continue their careers in the maritime industry.

These outcomes represent the ultimate indicators of whether training systems achieve their intended objectives sustainably. The model assumes a causal pathway in which training-related inputs influence human-centered mechanisms, which in turn affect operational and workforce outcomes. Specifically, increased training exposure and not adequately governed training systems are expected to negatively affect psychological detachment and recovery, thereby contributing to fatigue. Reduced recovery is, in turn, associated with lower perceived well-being and diminished retention intentions. At the same time, training is expected to contribute positively to safety outcomes when it is perceived as relevant, effective, and appropriately delivered. Importantly, the model recognizes that training delivery mode and governance quality may act as moderating factors. For example, digital or hybrid training formats may reduce logistical burden and improve flexibility, but only when accompanied by clear scheduling and realistic workload expectations. Conversely, poorly managed training systems may escalate fatigue and undermine recovery regardless of delivery mode. The proposed framework contributes to maritime research by explicitly integrating competence assurance and fatigue management within a single analytical model. By linking training demands to recovery processes and downstream outcomes, the model provides a structured basis for evaluating the unintended implications of training systems driven by compliance. This approach supports a shift towards more balanced, human-centered training practices that align safety objectives with seafarer wellbeing.

4. Questionnaire-based operationalization framework

To empirically examine the relationships defined in the conceptual model, a structured questionnaire framework was developed to operationalize the key constructs related to training demands, recovery processes, and associated outcomes. Given the multidimensional nature of the research problem, the questionnaire approach enables the systematic collection of subjective perceptions and experiences of seafarers, which are essential for evaluating both training effectiveness and its human-centered impacts. The instrument is designed to capture not only the perceived effectiveness of STCW refresher training, but also the broader implications of both STCW and non-STCW training demands on seafarers' shore-leave recovery, fatigue, and wellbeing. In doing so, it provides a practical means of assessing the interaction between competence assurance and recovery protection within real operational contexts. Figure 2 provides the questionnaire logic, including the input and output variables.

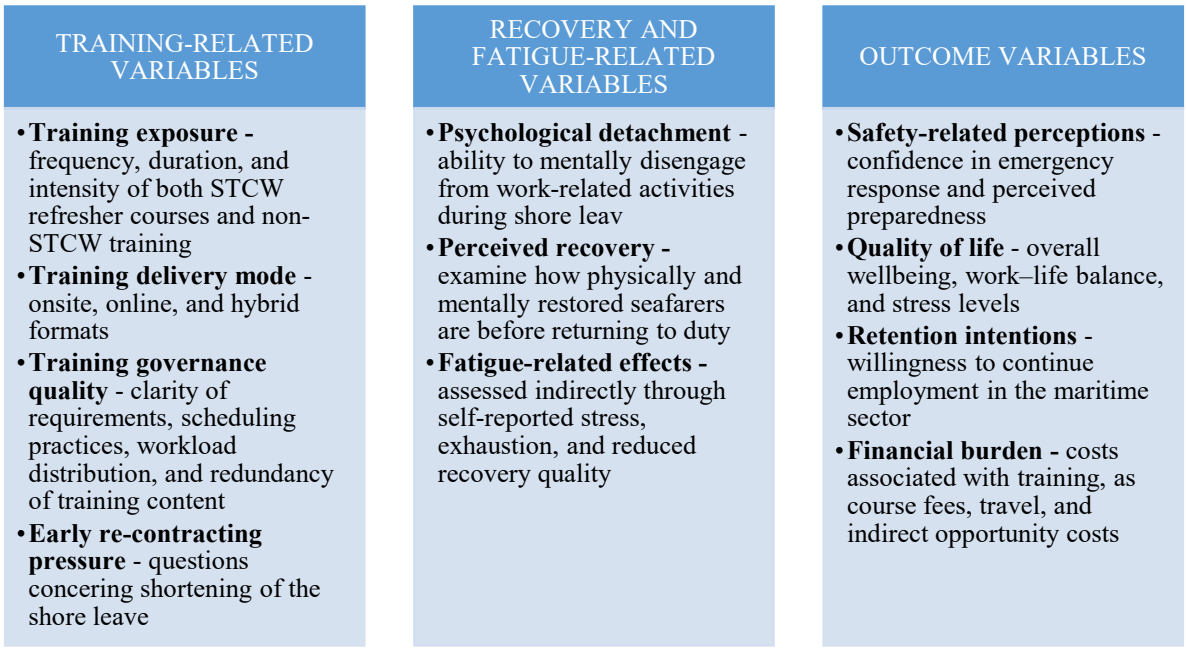


Figure 2. Structure of questionnaire variables aligned with conceptual model.

The questionnaire is primarily based on the Likert scale evaluation methodology to assess perceptions and experiences across the defined constructs. This approach allows the quantification of subjective variables such as recovery, fatigue, and perceived effectiveness, which cannot be directly measured through objective indicators. Where appropriate, categorical variables are used to capture structural aspects of training (delivery mode, training frequency), enabling comparative analysis across different training configurations. The combination of quantitative scales and categorical indicators supports both descriptive and inferential analysis of the relationships proposed in the conceptual model.

5. Discussion and conclusion

This paper addresses an increasingly relevant issue in maritime research and training by focusing on the relationship between training requirements and seafarers' ability to recover during shore leave. While the STCW Convention, IMO fatigue guidance, and the Maritime Labour Convention each provide important guidance on competence, safety, and welfare, they are predominantly implemented as separate regulatory policies. In practice, however, these dimensions are closely interconnected, and their interaction remains insufficiently explored within a unified analytical framework. A central argument of this study is associated with the fact that training should not be viewed solely as a compliance requirement, but also as a form of organizational workload. When training obligations are placed within periods intended for rest, they may interfere with recovery processes and contribute to fatigue, particularly in the case of refresher training and courses imposed by the company. This creates a structural discrepancy within the system, where training is intended to enhance safety through competence development while under certain conditions, it may reduce the human capacity required for safe performance.

Within the proposed framework, it becomes evident that not all training systems can be expected to have the same impact on seafarer recovery and fatigue. The way training is organized emerges as a critical factor, potentially as important as the volume of training itself. From this perspective, training delivery mode does not inherently determine outcomes, but rather shapes how training demands interact with seafarers' recovery processes, regardless of the training formats applied onsite, online, or hybrid. This perspective challenges the common assumption that increasing digitalization of training automatically leads to improved efficiency and reduced burden. However, the aforementioned also challenges the assumption that increasing training intensity inherently leads to improved safety outcomes. While digital and hybrid training models may reduce logistical and time-related constraints, their effectiveness depends on how they are integrated into seafarers' work-rest cycles. If inadequately scheduled or poorly aligned with shore-leave periods, such models may shift or redistribute workload rather than significantly reduce it, thereby reinforcing risks related to fatigue. This highlights the importance of training governance as a key moderating factor, influencing whether training

systems support or undermine seafarer wellbeing. The framework developed in this study has several practical implications for different stakeholder groups. For maritime administrations, it provides a basis for evaluating how competence requirements are implemented in practice, beyond formal compliance. For training providers, it emphasizes the importance of ensuring relevance, efficiency, and avoidance of unnecessary repetition in training programs. For shipping companies, it underlines the need to manage training demands as part of the overall workload, particularly in relation to shore leave and re-contracting practices. From a broader perspective, the proposed framework contributes to the ongoing discussion on the human element in maritime operations by highlighting that safety cannot be understood solely as a function of competence, but also as a function of adequately protected recovery and wellbeing. This suggests that future policy and regulatory developments should move towards more integrated approaches, where competence assurance and fatigue management are considered as mutually dependent rather than independent objectives. As this study is conceptual in nature, the relationships identified within the framework have not yet been empirically validated. Future research should focus on applying the proposed questionnaire to test these relationships across different operational contexts, vessel types, and seafarer profiles. Such empirical work would provide a more robust basis for evaluating how training practices influence recovery, fatigue, and long-term workforce sustainability. In conclusion, this paper provides a structured foundation for evaluating maritime training systems beyond compliance by explicitly linking training demands with recovery processes and human-centered outcomes. The proposed framework represents a step towards a more integrated and balanced approach to maritime training, where safety is achieved not only through competence development, but also through the protection of seafarer wellbeing.

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Maritime Competences for the Future: Role of Internationalization in Transversal Skills Development

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Abstract: Innovations concerning technological progress and globalization in the maritime industry have resulted in rapid advancements within the field, implying that the term of maritime competencies should be revised in its entirety. This article aims at addressing the issue of internationalization and its effect on transversal competencies in maritime education and training programs. With the increase in the degree of internationalization within the sector, technical skills alone will not be sufficient to ensure the future success of maritime practice, since soft skills such as intercultural communication, flexibility, problem solving, and leadership play an increasing role in modern maritime practice. The current research explores the role of internationalizing processes in maritime education in terms of improving transversal competencies within maritime education and training. The article concludes with several recommendations on the ways of integrating internationalization into maritime education programs to foster the acquisition of transversal skills. The research employs a mixed-methods approach including both case study analysis and surveying data. The results show considerable improvements in transversal competencies of students who have international experience.

Keywords: Maritime Education; Transversal Skills; Internationalization; Competence Development

1. Introduction

It should be noted that the marine industry is experiencing an important period of transformation, where the advancement of technology, regulatory requirements, and globalization are forming organizational models of operation. Automated ships, digital navigation, and the merging of fleets management and the relations that arise in doing so lead to a transformation in traditional working practices, while regulatory instruments like IMO 2020 and the Ballast Water Management Convention adopted by the International Maritime Organization create new conditions of work for maritime practitioners. On the other hand, during the process of change and development in the maritime industry, we observe growing diversity within its workforce, which is particularly notable aboard ships, where there can be people from several nations serving in one crew.

Change brings about new conditions of practice for maritime practitioners, who need to possess high levels of technical competence and the capacity for the use of transferable skills, allowing them to increase their agency in multicultural and complex contexts. It should be acknowledged that, traditionally, many programs in maritime education and training viewed technical competencies as a priority when it came to foundational knowledge and skills. On the other hand, there has been an awareness building that such skills alone will not be sufficient in addressing the evolving issues in the current industry.

This new perspective is recognized by the International Maritime Organization in the form of a new amendment to the STCW Convention. This revision covers not only technical skills, but also leadership skills and decision-making skills.

Nevertheless, the pedagogical approaches employed by maritime professionals when acquiring these crucial transversal competencies remain underexplored in maritime educational research.

This paper argues that internationalization – defined as the incorporation of the international, intercultural, and global dimension into educational programs – is an effective, albeit underutilized, mechanism for fostering the required transversal skills in professional mariners.

2. Literature Review

According to Deardorff (2006), international educational experiences have helped in developing "intercultural competence" among students, while Potts (2015) emphasized that students participating in exchange programs acquired better communication, adaptability, and problem-solving skills. As per Jones (2013), there exists a strong correlation between international educational experiences and outcomes in employment opportunities especially in industries that are interfacing internationally.

Internationalization of Maritime Education – It is important to note that the maritime industry, by its very nature, is a global industry. However, it can be observed from the literature that very few academic studies have focused on the internationalization of maritime education. For instance, most of the academic literature on the internationalization of maritime education focuses on internationalizing the curriculum (e.g., Severance and Yoffee, 2017) or improving the English language skills of maritime education program students (e.g., Ding and Liang, 2015). Notable exceptions are provided by the studies of Solesvik (2018) on the international partnership models in the Nordic maritime academies and Gekara (2019) on the transnational maritime education programs.

None of these academic works consider the experiences related to internationalization in the maritime field and its impact on developing the transversal skills of maritime education program students. This is an important research direction in light of the increasingly multicultural operating environment in the maritime industry and increased emphasis on non-technical competencies in the maritime field. As per Berg (2018), "maritime profession is by nature international, but the maritime education system remains astonishingly national in orientation and delivery." There is ample scope for the maritime educational institution to benefit from this situation while educating the future maritime professionals.

3. Methodology

Research Design

A mixed methodology was used in this research to determine the connection between the strategies for internationalization and development of transversal skills in maritime education. There were three stages in the implementation of this methodology. Stage 1 – Qualitative stage. Case study research on internationalization strategy implemented at Batumi Navigation University was done in order to determine the most common strategies for internationalization and approaches used within this process. Stage 2 - Quantitative stage.

The survey was undertaken among students enrolled in maritime studies (n = 287), both current and former, in order to establish the impact of international experiences on transversal skills including intercultural communication, adaptability, problem solving, and resilience. The methodology is appropriate for addressing the research problem.

Survey Sample and Data Collection

The quantitative phase involved a survey of 287 respondents, including current students and recent graduates of Batumi Navigation University. Data were collected between January and March 2026. Participants were divided into two groups: (1) 80 respondents (27.9%) who had participated in at least one internationalization activity (student exchange, international internship, virtual international collaboration, or international training programme), and (2) 207 respondents (72.1 %) without such experience.

Participation in the survey was voluntary and anonymous. The questionnaire consisted of demographic questions and self-assessment items related to transversal skills development.

Measurement of Transversal Skills

Transversal skills were measured using a five-point Likert scale (1 = very low; 5 = very high). Respondents assessed their perceived level of competence in the following dimensions: Intercultural communication; Adaptive problem-solving; Leadership and teamwork; Learning agility; Professional resilience. Mean scores were calculated for each competency area and compared between respondents with and without international experience.

Qualitative Data Collection

The qualitative phase included a case study of Batumi Navigation University and two focus group discussions involving 16 participants who had completed international mobility programmes. Each focus group consisted of 8 participants and lasted approximately 60 minutes. Discussions explored participants' perceptions of how international experiences influenced their communication skills, adaptability, problem-

solving ability, and professional development. Thematic analysis following Braun and Clarke (2006) was used to identify recurring themes within the qualitative data.

4. Results

The findings of the study are presented through a combination of qualitative observations and quantitative results. Quantitative findings are summarized in Tables 1–3 and Figures 1–2, while qualitative insights are derived from the focus group discussions and case study analysis.

Batumi Navigation University and Its Internationalization Approaches

Batumi Navigation University provides a clear example of how internationalization can be effectively introduced into maritime education by incorporating global elements into its programs. First of all, the university implements a comprehensive approach that involves a range of actions to promote internationalization.

On the one hand, an international outlook is introduced into the educational process not only based on the requirements of IMO and STCW but also considering maritime culture and practice from other regions around the world. On the other hand, many relationships have been established between the university and maritime schools and universities in Turkey, Ukraine, Bulgaria, Western Europe, etc. Moreover, one cannot but mention the extracurricular side of studying and interaction with the maritime environment through internships abroad, cooperation with shipowners in the Black Sea region, etc.

In addition, internationalization is carried out through language training and certification of graduates. Thus, there are certain factors that help achieve success in implementing internationalization policies at the university.

These include strong leadership within the institution, proper investment in international activities, alignment with educational goals, involvement of industry stakeholders, ongoing evaluation of outcomes, and the strategic advantage of the university's geographic location.

Internationalization Initiatives and Development of Transversal Skills

Further analysis of specific internationalization activities shows that they contribute differently to the development of transversal skills. Table 1 summarizes how these initiatives relate to particular competencies, based on both qualitative findings and survey data.

Table 1. Contribution of internationalization activities to the development of transversal skills.

Internationalization Initiative	Most Effectively Developed Competencies	Effectiveness (1–5)
Semester-long exchange programs	Intercultural communication; adaptability; autonomy	4.7
Short-term intensive programs (2–4 weeks)	Teamwork; networking	3.9
International internships	Problem-solving; communication; resilience	4.8
Virtual international collaborations	Digital communication; project management; remote teamwork	3.5
International faculty exchange	Global awareness; broader perspective	3.3
Internationalized curriculum content	Knowledge integration; cultural awareness	3.0

The effectiveness scores presented in Table 1 represent the average ratings provided by survey respondents regarding the perceived contribution of each internationalization activity to their transversal skills development. Ratings were measured on a five-point scale, where 1 indicated very low effectiveness and 5 indicated very high effectiveness.

In general, the findings suggest that greater immersion, such as through internships and full-semester exchanges, is associated with stronger development of transversal skills. At the same time, the longer students are exposed to international environments, the more noticeable their skill development becomes across all areas.

Transversal Skills Development Outcomes

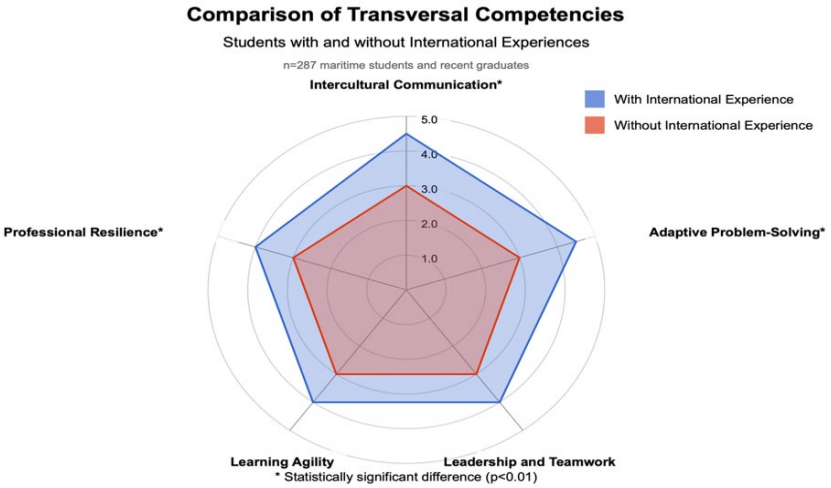


Figure 1. A radar chart comparing competency levels between the two groups.
Source: Author's survey data (2026).

Table 2. Comparison of self-assessed transversal competencies between respondents with and without international experience.

Competency	With International Experience	Without International Experience	Statistical Difference
Intercultural Communication	Higher	Lower	Significant ($p < 0.01$)
Adaptive Problem-Solving	Higher	Lower	Significant ($p < 0.01$)
Leadership and Teamwork	Slightly Higher	Lower	Not statistically significant
Learning Agility	Slightly Higher	Lower	Not statistically significant
Professional Resilience	Higher	Lower	Significant ($p < 0.01$)

Source: Author's survey data (2026).

The obtained data indicated some disparities between students and graduates with or without international experience. It can be seen that the former demonstrated higher levels of confidence regarding intercultural communication, adaptation to unknown environments, and resilience in stressful conditions. Some progress in team collaboration, leadership and learning ability was observed too; however, it failed to become statistically significant.

The statements by focus group members may be helpful in further interpreting the findings. As stated in many responses, being in a new country and collaborating with culturally diverse colleagues required a person to think differently, develop new skills and approaches. For example, one student claimed that adjusting to the new educational system made them more flexible and adaptive to changes. One recently graduated respondent added that interacting with colleagues from maritime cultures led to questioning the established patterns and finding new solutions.

From the perspective of employment, the benefits provided by internationalization were evident too. According to the data collected, most international graduates (92%) got employed in the industry within six months after receiving their diploma compared to 74% among other students. Besides, those graduates were hired for positions with more responsibilities and received promotions in seven months faster on average.

Employment outcomes were assessed through a graduate follow-up survey conducted among respondents who had completed their studies within the previous three years. Participants reported employment status, time required to obtain their first maritime position, and career progression indicators, including promotion history and level of responsibility within their organizations.

Table 3. Employment outcomes of graduates with and without international experience.

Indicator	With International Experience	Without International Experience
Employment within six months after graduation	92%	74%
Promotion speed	Approximately 7 months earlier	Baseline
Access to positions with higher responsibility	More frequent	Less frequent

Source: Graduate follow-up survey (2026).

The same thing applies to employers, who valued their ability to adapt to new conditions and solve arising problems. Thus, internationalization appears to be beneficial not only from an academic but also practical perspective, helping students enter the labor market successfully.

Specifically, international graduates had better chances to receive jobs at shipping companies located in the Black Sea region, where cross-border cooperation is common practice. Taking all aspects into account, it can be concluded that internationalization is associated with improved professional outcomes and may contribute to graduates' professional performance.

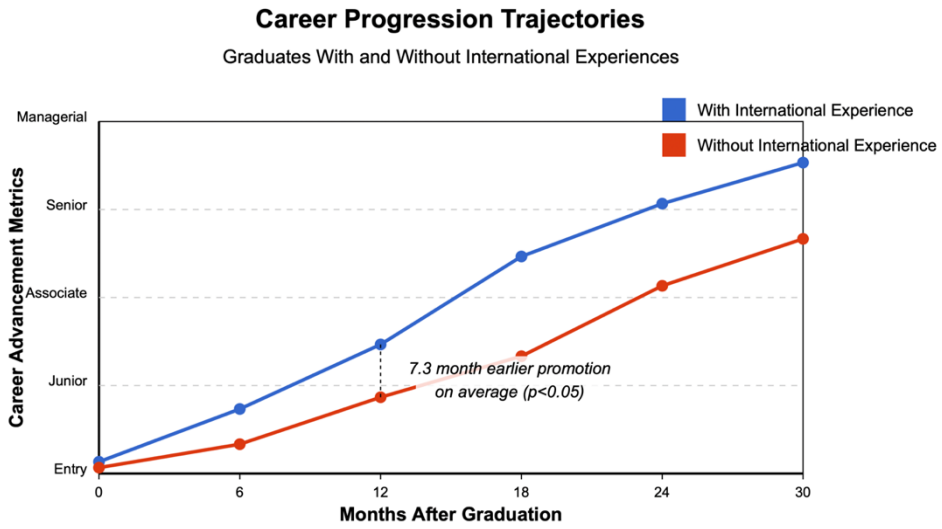


Figure 2. A line graph comparing career progression between two groups over time.

Source: Author's survey data (2026).

Overall, the results indicate that the internationalization strategies implemented at Batumi Navigation University play an important role in improving graduates' chances of employment and helping them adapt more effectively to the demands of the maritime industry.

5. Limitations

Several limitations should be acknowledged. First, the study was conducted primarily within a single maritime higher education institution, which may limit the generalizability of the findings. Second, the study relied largely on self-reported perceptions of transversal skill development. Third, students who chose to participate in international activities may already possess characteristics that support stronger professional development outcomes. Future research should include multiple maritime institutions, longitudinal designs, and objective measures of competence development.

6. Discussion

Taking into account the results received during the current study, it can be stated that internationalization plays an important role in the process of formation of transversal competencies for students enrolled in the maritime sector. According to the data provided in Section 4, those participants who had some international experience demonstrated higher indicators in terms of their ability to adjust, solve problems and communicate interculturally.

It is possible to argue that internationalization can facilitate the acquisition of transversal skills since it provides students with opportunities to experience various situations and deal with them in such a way that they need to adjust their behaviors, ways of communication and decision-making processes. Thus, it is clear that internationalization appears to support the process of transformative learning when individuals acquire new experiences that change the ways they think.

Although short-term international programmes demonstrated lower effectiveness scores than semester-long exchanges and international internships, they still provide valuable opportunities for exposure to intercultural environments. Future programme design should focus on increasing structured reflection activities, project-based collaboration, and follow-up mentoring in order to maximize the developmental impact of short-duration mobility experiences.

Additionally, internationalization adds certain complexity that cannot be achieved through usual classroom learning. In this regard, the task of students is to face challenges related to internationalization and deal with them based on their knowledge and understanding. Therefore, the findings suggest that such an approach may help to develop some useful skills and prepare professionals for their future practice.

Finally, the data revealed that the effectiveness of internationalization depended upon the approaches used in this process. To put it another way, internship and extensive exchanges were more efficient than short-term and theoretical practices. Thus, it may be stated that internationalization requires its own organizational approach.

Summing up all said above, one may assume that internationalization cannot be regarded as a marginal issue, but rather as a process that presupposes preparation of specialists for their further professional activity. This assumption agrees well with empirical data obtained in part 4.

7. Conclusions

In conclusion, this research highlighted the benefits that internationalization offers when it comes to preparing the maritime professionals of tomorrow by developing their transversal competencies. Specifically, it presented the analysis of the maritime international education programs offered by Batumi Navigation University compared to industry needs. Concerning the structured internationalization approaches, they appeared to be effective when developing transversal competencies such as intercultural communication, adaptability, decision-making, and leadership. Thus, the results suggest that being exposed to the diverse international environment can effectively promote and fasten the development of transversal competencies especially in terms of cultural awareness, flexibility in communication, and adaptability in decision-making. Moreover, the findings suggest that graduates who participated in international education activities tend to report higher employability and stronger career advancement prospects in the maritime industry. The findings suggest that internationalization in education may support the creation of non-traditional forms of teaching and learning, which are applicable in practice and involve imagining oneself and acting in an auxiliary role to develop complex programs of transversal skills through different forms of learning based on one's experience. This statement is particularly true about Georgian maritime education since international experience helps maritime students to make a connection between national maritime tradition and industry practices. The proposed framework of internationalization initiatives for the maritime education program will help BNU, Batumi and other maritime education establishments implement their initiatives aimed at maximized development of transversal skills for professionals to operate in the changing maritime industry.

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Turnover Intention and Quiet Quitting among Seafarers: The Role of Demographic and Job-Related Characteristics

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Abstract: The global maritime industry faces persistent challenges in workforce retention and engagement, underscoring the need to understand factors shaping seafarers' organisational attitudes and behavioural outcomes. This study examines how demographic (age, gender, nationality, education, marital/partner status, and children) and job-related factors (seafaring tenure, tenure within the current company, vessel type, onboard position, and income) relate to turnover intention (TI) and quiet quitting (QQ). TI refers to considering leaving an employer, while QQ denotes reduced engagement and performing only minimum required tasks. Data were collected from 508 active seafarers, primarily from South-Eastern Europe, using convenience sampling. TI was significantly associated with age, seafaring experience, and tenure with the current company, with higher levels among younger and less experienced seafarers. It was also associated with education, income, and onboard position, with higher TI among more educated, lower-paid seafarers, and senior deck personnel compared to senior engineers. Croatian seafarers reported higher TI than Greek seafarers. QQ showed similar patterns, being higher among younger and less experienced seafarers, and was additionally associated with income and having children, with lower QQ among higher-income seafarers and those with children. Despite sampling limitations, the findings provide directions for future research and practical implications for understanding withdrawal-related outcomes among seafarers.

Keywords: seafaring, turnover intention, quiet quitting

1. Introduction

Seafaring involves demanding and stressful working conditions (Brooks and Greenberg, 2022; Carrera-Arce et al., 2025; Li et al., 2022; Nittari et al., 2024; Slišković, 2017), which can negatively affect seafarers' well-being as well as their organisational attitudes and behavioural outcomes, particularly turnover intention (TI) and quiet quitting (QQ). TI refers to a conscious intention to leave an organisation based on evaluations of work conditions and alternatives (Dhoopar et al., 2026), whereas QQ denotes a behavioural form of withdrawal in which employees continue to fulfil formal job requirements while withdrawing discretionary effort, initiative, and motivation (Galanis et al., 2023; Serenko, 2024). These outcomes can be understood within the Job Demands–Resources (JD–R) framework, which highlights how job demands (e.g., workload, fatigue, isolation) and resources (e.g., autonomy, leadership support, onboard social support) shape work outcomes (Bakker et al., 2023). However, the present study takes a more distal perspective by examining demographic and structural job characteristics as correlates of TI and QQ.

Seafarers' TI is particularly relevant due to workforce shortages and projected gaps (BIMCO and ICS, 2021), with consequences for crew stability, costs, and safety (Fin and Harito, 2025). Research shows that TI among seafarers is linked to high job demands and strain, low job satisfaction and poor conditions, weak commitment and career prospects, and family pressures and isolation (Amathalai, 2024; Bao et al., 2021; Fin

and Harito, 2025; Garciano and Garciano, 2023; Gu et al., 2020; Hwang, 2022; Kim and Lee, 2011; Özdemir, 2020; Uçak and Maşalacı, 2025).

In contrast, research on QQ in seafaring remains very limited. A recent study by Slišković et al. (2026) found that burnout was associated with higher levels of QQ both directly and indirectly through TI. Despite this initial evidence, little is known about demographic and job-related correlates of QQ among seafarers. However, given that QQ is conceptually rooted in work disengagement, psychological withdrawal, and minimal in-role performance (Serenko, 2024), existing maritime research on work engagement may nevertheless provide indirectly relevant insights, as it reflects behavioural patterns that may partially overlap with manifestations associated with QQ. Findings show that engagement is strengthened by job resources such as supportive leadership, autonomy, feedback, fair compensation, onboard facilities, and positive social environments, while it is undermined by high demands including fatigue, long working hours, isolation, and limited recovery opportunities (Ariza-Montes et al., 2021; Brooks and Greenberg, 2022; Chung et al., 2017; Hayes-Mejia and Stafström, 2024; Glaveli et al., 2025; Jonglertmontree et al., 2022; Kundori et al., 2025; Qi et al., 2024; Radic et al., 2020; Rayos and Borbon, 2022; Uğurlu et al., 2025). Lower engagement has been associated with reduced retention, performance, and safety-related behaviour (An et al., 2020; Bhattacharya, 2015; Hayes-Mejia and Stafström, 2024; Rameshkumar, 2020; Senbursa and Kılıç, 2024; Uğurlu et al., 2025).

In this context, it is important to emphasise the novelty of the QQ construct and its distinction from related concepts such as work disengagement, withdrawal behaviours, burnout, and organisational commitment. Although QQ is conceptually related to these constructs, it represents a distinct behavioural pattern. Burnout refers to emotional and psychological exhaustion, whereas organisational commitment reflects employees' psychological attachment to their organisation. Similarly, disengagement captures a broader reduction in cognitive, emotional, and behavioural involvement in work. In contrast, QQ is a specific behavioural pattern in which employees meet formal job requirements while deliberately reducing discretionary effort, initiative, and motivation (Galanis et al., 2023; Serenko, 2024; Slišković et al., 2026). Thus, QQ can be understood as a form of withdrawal focused on behavioural boundary-setting rather than organisational exit or full disengagement.

In summary, prior literature has extensively documented the role of psychosocial factors, including job demands and resources, in shaping work-related attitudes and behavioural outcomes within maritime contexts. Building on this, the present study examines the role of demographic and job-related characteristics. Focusing on both individual and structural factors enables the identification of seafarer profiles that may be more susceptible to withdrawal-related outcomes, offering possible practical implications for targeted retention and engagement strategies aimed at supporting safer operations and workforce stability.

Existing maritime research suggests that demographic characteristics show meaningful, although sometimes mixed, associations with TI. Age appears particularly relevant: younger seafarers generally report higher TI, while older seafarers tend to show greater retention (Agbator and Olori, 2020; Bao et al., 2021; Kim and Lee, 2011). Furthermore, seafarers with higher levels of education have sometimes been found to report higher TI than those with lower qualifications (Kim and Lee, 2011; Reig-Botella et al., 2022). Family circumstances also shape retention patterns. Married seafarers with children may exhibit lower TI, but family responsibilities can also contribute to higher TI and influence career-related decisions, particularly among younger employees (Agbator and Olori, 2020; Bao et al., 2021; Kim and Lee, 2011). Evidence regarding gender and nationality remains comparatively limited and mixed. Some studies suggest that women may report higher intention to stay in the seafaring profession than men (Agbator and Olori, 2020), while research on women seafarers has focused more on structural barriers and underrepresentation than on turnover outcomes (Narayanan et al., 2023).

Job-related characteristics also play an important role in explaining TI and related outcomes. Longer seafaring experience and stronger attachment to a company are generally associated with lower stress and higher retention, while work-related differences in stress and job satisfaction across departments may also be relevant (Jonglertmontree et al., 2022; Wu et al., 2021). Employment conditions such as income and reward systems shape job satisfaction and performance and are repeatedly linked to TI (Fin and Harito, 2025; Yuen et al., 2018). Some studies suggest that position or job function can shape TI through differences in role demands and job satisfaction, while organisational context, such as vessel or company characteristics, may shape commitment and well-being, although findings on vessel type itself remain inconsistent (Karakasnaki et al., 2025; Rameshkumar, 2020; Sandberg et al., 2020).

As noted earlier, empirical evidence on QQ in the maritime context remains limited, with only one recent study examining the construct directly (Slišković et al., 2026), and evidence on the role of demographic and job-related characteristics on even the related concepts is extremely limited. Examining these characteristics thus offers a novel opportunity to explore potential correlates of QQ in a high-demand occupational setting.

Accordingly, the study addresses the following ***research questions***:

(1) How are ***demographic characteristics*** (age, gender, nationality, education, marital/partner status, parenthood) associated with ***TI*** and ***QQ*** among seafarers?

(2) How are ***job-related characteristics*** (total seafaring experience, tenure in the current company, vessel type, onboard position, income level) associated with ***TI*** and ***QQ*** among seafarers?

2. Methodology

Data were collected online between March 30 and June 14, 2025, from a non-random international sample of 508 seafarers recruited via companies, unions, training institutions, and social networks. Eligibility required at least one year of seafaring experience. Participation was voluntary and anonymous, with informed consent obtained electronically. Table 1 summarizes the sample's demographic, professional, and family characteristics.

The questionnaire was administered in English. After the first section on demographic, professional, and family characteristics (see Table 1), the questionnaire administered the Quiet Quitting Scale (Galanis et al., 2023), which measures behavioural and attitudinal indicators of reduced engagement at work. The nine-item scale evaluates behaviours such as completing only the minimum required tasks, avoiding additional responsibilities, reduced initiative, and decreased motivation. The final section administered the Turnover Intention Scale (Bhuian et al., 2005), previously applied in seafaring contexts (Senbursa and Kılıç, 2024). This three-item scale evaluates the likelihood of employees leaving their organisation, including both recurring thoughts of quitting and anticipated job search activity within the next year.

Table 1. Sample characteristics (N = 508).

Variable	Category	M ± SD (range) / n (%)
Age (years)		37.39 ± 10.95 (19–77)
Seafaring experience (years)		14.73 ± 10.19 (1–47)
Tenure at company (years)		7.02 ± 6.89 (0–42)
Gender	Male	484 (95.3)
Nationality	Greek	171 (33.7)
	Croatian	155 (30.5)
	Montenegrin	62 (12.2)
	Latvian	41 (8.1)
	Turkish	31 (6.1)
	Other European	30 (5.9)
	Other non-European	5 (1.0)
Education level	Basic/High school	69 (13.6)
	Merchant Marine Academy	219 (43.1)
	Bachelor's degree	146 (28.7)
	Postgraduate degree (Master/PhD)	70 (13.8)
	Other	4 (0.8)
Vessel type	Cargo	460 (90.6)
	Passenger	48 (9.4)
Job position	Senior deck personnel	274 (53.9)
	Senior engineering personnel	169 (33.3)
	Junior officers (deck/engine)	25 (4.9)
	Electro-technical officers	19 (3.7)
	Hotel/service personnel	5 (1.0)
	Other	16 (3.1)
Monthly income	< $3,000	60 (12.9)
	$3,000–$7,000	238 (51.2)
	$7,000–$11,000	114 (24.5)
	> $11,000	53 (11.4)
Marital/partner status	Yes	362 (72.3)
Having children	Yes	253 (50.8)

3. Results

Descriptive statistics for the study variables are presented in Table 2. Skewness and kurtosis values indicated no substantial deviations from normality, supporting the use of parametric analyses. Internal consistency was acceptable for QQ and excellent for TI. Given the response range of the scales, on average participants reported low to moderate levels of QQ and moderate levels of TI. Variability was greater for TI than for QQ, indicating larger individual differences in TI. The average level of quiet quitting exceeded the threshold proposed for identifying quiet quitting tendencies (Galanis et al., 2024), suggesting that such tendencies were present in the sample.

Table 2. Descriptive statistics and reliability of the used scales.

Scales	M ± SD	Min–Max	Skewness	Kurtosis	Cronbach's α
QQ	2.36 ± 0.58	1.00–4.67	0.39	0.39	0.75
TI	2.85 ± 1.17	1.00–5.00	0.13	-0.84	0.92

In order to address main research questions, the correlational analysis examined how demographic and job-related characteristics are associated with TI and QQ. The number of participants varied across variables due to missing data, which is reported in the table, and should be considered when interpreting the results. Furthermore, because some categories had a small number of participants (see Table 1), only Croatian and Greek seafarers were included in the correlational analysis related to nationality, and only seniors, i.e. officers (deck vs. engineering and electro-technical) were included in the correlational analysis related to onboard position. Engineering and electro-technical officers were combined into a single category due to the small number of electro-technical officers in the sample and because both groups belong to the same engine/technical department with similar onboard operational contexts.

Pearson correlation coefficients showed that several demographic and job-related characteristics were significantly associated with TI and QQ (Table 3). With respect to demographic characteristics, younger seafarers reported higher levels of TI and greater tendencies toward QQ. Seafarers with children demonstrated lower levels of QQ. Higher educational attainment was associated with increased TI, while nationality was also related, with Croatian seafarers reporting higher TI compared to Greek seafarers. Gender and marital or partner status were not significantly associated with either outcome. Regarding job-related characteristics, seafarers with less total experience and shorter tenure with their current company exhibited higher TI and QQ. Income level was inversely related to both outcomes, indicating that seafarers with lower income reported higher TI and higher QQ. Onboard position was associated with TI, with deck officers reporting higher TI compared to engineering and electro officers, while vessel type was not significantly associated with either outcome. Although noted correlations reached statistical significance, most were small in magnitude according to conventional benchmarks. Given the number of statistical tests performed, the possibility of Type I error should be considered when interpreting individual p-values.

To examine the independent contribution of the identified correlates and to determine which predictors remained associated with the outcomes after controlling for the effects of the other variables, two multiple regression analyses were conducted. In line with the correlational results, only variables that demonstrated significant bivariate associations with the respective criterion variables were included in the regression models. For TI, the following predictors were entered into the model: age, total seafaring experience, tenure with the current company, nationality, education, onboard position, and income. For QQ, the predictors included age, total seafaring experience, tenure with the current company, parenthood status, and income.

The regression results showed that the model explained 5.4% of the variance in TI, with nationality and income emerging as significant independent predictors, as indicated by the standardised regression coefficients (β) reported in Table 3. For QQ, the model explained 4.7% of the variance, with income being the only significant predictor, as shown by the standardised regression coefficients (β) in Table 3. Overall, although several variables were significantly correlated with the outcomes at the bivariate level, the regression analyses suggest that these associations overlap substantially, resulting in a relatively modest proportion of explained variance in both TI and QQ.

Table 3. Pearson correlations and multiple regression analyses predicting TI and QQ.

Variable	N	TI (*r*)	TI (*β*)	QQ (*r*)	QQ (*β*)
Age	508	-.136**	-.139	-.137**	.092
Total seafaring experience	508	-.113*	.111	-.173**	-.110
Tenure with current company	508	-.100*	-.022	-.132**	-.090
Gender (male vs. female)	508	-.040	—	-.002	—
Marital/partner status	501	.040	—	-.085	—
Having children	498	-.032	—	-.132**	-.049
Nationality (Croatian vs. Greek)	396	.198**	.214**	.075	—
Education	504	.101*	.090	.026	—
Onboard position (Deck vs. Engine and Electro officers)	462	-.100*	.018	-.044	—
Income	465	-.162**	-.176*	-.150**	-.150**
Vessel type (Passenger vs. Cargo)	508	.056	—	.013	—
Adjusted R²			.054		.047

Note. r = Pearson correlation coefficient; β = standardised regression coefficient. Predictors were included in the regression models only if they showed a significant bivariate association with the respective outcome. Dashes indicate variables not included in the regression model; * $p < .05$, ** $p < .01$.

4. Discussion

This study examined how demographic and job-related factors relate to TI and QQ in seafaring. Consistent with previous research (Agbator and Olori, 2020; Bao et al., 2021; Jonglertmontree et al., 2022; Kim and Lee, 2011; Wu et al., 2021), younger and less experienced seafarers reported higher levels of TI as well as greater tendencies toward QQ. While the association between these characteristics and TI has been well documented, their relationship with QQ has received little empirical attention to date. Obtained associations may reflect differences in adaptation to the demanding work environment at sea, potentially linked to limited professional experience, less established social networks onboard, or higher career mobility aspirations. Similarly, seafarers with shorter tenure in their current company were more likely to consider leaving or demonstrate QQ, highlighting the potential role of organisational attachment and familiarity in relation to retention.

Educational attainment and onboard position were significantly associated with TI in our study, suggesting that highly educated seafarers and deck officers may have different career expectations and/or perceive greater opportunities outside their current employment. These results align with previous research indicating that more highly educated seafarers report higher TI than those with lower qualifications, and that job position or role can shape TI through differences in career prospects and responsibilities (Kim and Lee, 2011; Reig-Botella et al., 2022). Nationality differences were observed, with Croatian seafarers reporting higher TI than Greek seafarers. However, these findings should be interpreted cautiously and as exploratory, as the present study did not include variables that could explain such differences (e.g., cultural, regulatory, or labour market factors), which have been highlighted as relevant in previous research (Katsounis et al., 2023). Furthermore, parenthood in our study was associated with lower levels of QQ, which may reflect differences in work-related attitudes or self-regulatory processes.

Income level emerged as a significant correlate of both TI and QQ, with lower-income seafarers tending to report higher levels of both outcomes. This pattern is in line with broader findings on the role of economic factors in employee retention and disengagement (Fin and Harito, 2025; Yuen et al., 2018). This finding

underscores the continued importance of adequate and fair compensation, particularly in a highly demanding and stressful occupational context.

It should be noted that the observed associations were generally small in magnitude. In addition, the regression models explained only a limited proportion of the variance in TI and QQ, suggesting that these outcomes are likely shaped by a broader range of factors beyond the demographic and job-related characteristics examined in the present study. Therefore, the observed associations should be interpreted cautiously and viewed as only one part of a more complex set of factors related to withdrawal-related outcomes among seafarers. The regression analyses further indicated that most demographic and job-related variables did not remain significant when examined simultaneously. Income emerged as the most consistent predictor across both outcomes, while nationality remained significant only for TI. Overall, these findings highlight the importance of interpreting bivariate associations with caution and support the use of multivariate approaches in identifying the correlates that remain associated with TI and QQ after accounting for other variables.

Overall, these findings highlight the importance of personal, professional, and contextual factors in explaining TI and QQ among seafarers. They also extend the emerging maritime literature on QQ, suggesting that, alongside burnout and TI (Slišković et al., 2026), demographic and job-related characteristics may be associated with QQ tendencies among seafarers. The results complement general recommendations for building healthier (Slišković and Katsounis, 2025) and more employee-friendly organisations (Senbursa and Kılıç, 2024) by identifying groups that may be more vulnerable to the demanding conditions of maritime work and potentially at greater risk of withdrawal-related outcomes. Targeted support for younger and less experienced seafarers, competitive and transparent compensation, mentoring programmes, and attention to work–life balance may therefore represent relevant areas for organisational focus and future research in relation to TI and QQ, particularly given the potential implications of QQ for operational efficiency and onboard safety.

However, the findings should be interpreted in light of several limitations. The non-representative sample and the use of an English-language online survey may have introduced self-selection bias and limited the generalizability of the results. In addition, the cross-sectional, correlational design precludes causal inferences and does not allow conclusions about the direction of the observed associations. Future research should replicate these findings in larger and more diverse samples, including seafarers of different nationalities, ranks, and vessel types. Furthermore, given the number of statistical tests performed, some statistically significant findings may reflect Type I error. The results should therefore be considered exploratory and warrant replication in future studies. Finally, although the study was theoretically grounded in the JD–R framework, its empirical focus was primarily on demographic and structural job characteristics rather than specific job demands and resources. Future research should incorporate a broader range of JD–R indicators to better capture the mechanisms underlying turnover intention and quiet quitting in seafaring contexts. Longitudinal designs could provide insight into the development of TI and QQ over time, while qualitative approaches could further illuminate the motivations and contextual factors associated with withdrawal-related outcomes among seafarers.

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Mental Fortitude at Sea: Supporting Seafarers in Crisis Zones

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Abstract: Seafarers working in conflict areas require a high level of psychological resilience due to risks that are physical, geopolitical and often immediate. Safe navigation in such waters cannot be separated from the mental condition of the crew. The objective of this work is to raise awareness of the need for training programmes addressing conflict exposure, stress, high-pressure communication and mental-health awareness, so that seafarers can recognise danger in themselves and in others before situations deteriorate. The research draws on qualitative empirical data from 47 semi-structured interviews conducted between November 2023 and March 2026 across Egypt, Turkey, the Philippines and the UAE, analysed in NVivo using open, axial and thematic coding. Ethical clearance was obtained under Centurion University standards and the study was conducted in line with BERA and ESRC research ethics guidance. The study addresses seafarers' knowledge of legal rights and welfare services during periods of severe stress, compensation pathways, and the wider need for inclusive protective policies. The paper concludes with practical recommendations for organisations, maritime administrations and MET institutions to strengthen mental-health support for seafarers in high-risk waters.

Keywords: Seafarers; mental health; working environment; conflict zones; stress symptoms; diaspora; maritime ethics

1. Introduction

Seafarers face a compounding burden. The first layer fatigue, isolation, long working hours, inspections and the diaspora of months away from family is well documented (Oldenburg et al., 2010; Allen et al., 2008; Jepsen et al., 2015; Carotenuto et al., 2012; Tedesco et al., 2018). Depression, suicide risk and the particular silence surrounding seafarers' distress have been highlighted in earlier work (Iversen, 2012; Mellbye & Carter, 2017). What is new is that a commercial vessel may now sail from a normal port call and within days find herself ordered towards a JWC-listed war or near-war area (JWC, 2024), a mined coast, or a lane where merchant ships have recently been struck. The impact on psychological performance is not simply poor sleep; it is the knowledge that the next explosion may come without warning. The impact of accidents, lack of sleep, exhaustion and psychological resilience on shipboard performance has been observed in many earlier works (Valdersnes et al., 2017; Zhao et al., 2020).

This paper examines those newer mental stressors through a qualitative study of seafarers and family members over more than two years across multiple conflict zones. Mental welfare at sea is a safety matter: crew members who are unpaid, unable to contact home, or uncertain about compensation are not in the best condition to operate safely (McVeigh et al., 2019; Pauksztat et al., 2022; Lefkowitz & Slade, 2024). Recent work has shown that employers should not wait until crisis is onboard before acting on seafarer welfare (Sampson & Ellis, 2023). The starkest examples are the southern Red Sea near Bab El Mandab, the Black Sea following the war in Ukraine, the Houthi attacks on merchant ships, and the conflict that erupted in the Arabian Gulf in late February 2026.

2. Methodology

The data first centred on two conflict areas: the Southern Red Sea and the Black Sea near Ukraine. Semi-structured interviews were conducted in Suez, Egypt, and Manila, the Philippines, with injured seafarers and families of deceased seafarers; and in Istanbul with seafarers repatriated after bulk carriers suffered damage near Ukraine while attempting to load grain from Odessa. All seafarers interviewed without exception showed signs of severe stress, including intrusive recollections, sleep disturbance, hypervigilance and emotional

numbing. More recently, in March 2026, an additional set of data was collected through arranged telephone interviews with captains and officers stranded at the outer anchorages of Dubai and Fujairah.

2.1 Sampling and Recruitment

Criterion-based sampling was applied: inclusion criteria were active or recently active seafarer status, or immediate family membership of a deceased seafarer; direct exposure to one of the four conflict events under study; and ability to provide informed consent in English, Tagalog (with interpreter support), or Arabic. Recruitment was facilitated through manning agencies, seafarers' welfare centres, ITF Seafarers' Trust networks and IMO/Cardiff University contacts during official missions. Snowball sampling was used cautiously and discontinued once saturation was reached.

2.2 Ethical Considerations

The study was conducted in line with BERA Ethical Guidelines in 2018 and the ESRC Framework for Research Ethics in 2023, and received Centurion University ethical clearance. Each participant received a participant information sheet and provided informed consent. All identifying details names, ship names, IMO numbers and company names were anonymised at transcription. Audio recordings are stored in an encrypted, password-protected drive accessible only to the principal researcher and will be destroyed per university protocols.

2.3 Data Analysis

All 47 interviews (November 2023 – March 2026) were transcribed and analysed in NVivo using three-stage coding: open, axial and thematic. Travel to Istanbul, Egypt and the Philippines was jointly funded by the researcher, the IMO during official missions, and Cardiff University's SIRC. The 2026 Hormuz interviews were conducted by secured telephone with WhatsApp used to exchange consent forms. Tagalog interviews were conducted with the assistance of a bilingual welfare officer and an independent translator. Where the term PTSD appears, it refers only to cases formally diagnosed by attending medical staff; otherwise the study reports "stress-related symptoms consistent with post-traumatic stress responses".

3. Sample Accounts of Seafarers

3.1 Filipino Motorman — Red Sea attack, December 2023

> *"I was sleeping in my cabin, around 2 AM there was a huge sound of explosion and the fire alarms sounded; tried to get out of my cabin, the hallways were full of smoke, I think I lost consciousness trying to go to deck. I was hoping to be with my family for Christmas but was hospitalised for four weeks in Suez before they repatriated me back home."*

3.2 Indian Captain — Istanbul, Ukraine cargo run

"We were told to proceed to Odessa to load bulk grain after an agreement was struck between Turkey and Russia. It was very stressful for all my crew when we received orders to sail to this part of the world, but we can't refuse company orders. As we sailed out of Odessa fully loaded and after the Pilot disembarked, we were struck by a projectile that fell on the aft deck while my crew members were still sorting out the mooring lines. Sadly, one AB lost his life and two others sustained severe injuries. Why this happened to our ship? I still don't know." (text slightly modified to conceal company name and identities)

3.3 Bereaved Filipino wife of an AB — Manila, May 2025

"We now lost our breadwinner … my husband paid those trade unions here a lot of money to get on that good company with better salaries, then he came back to me in a box. He was always stressed when talking to me on the phone telling me that some ships were bombarded in the Red Sea — what am I going to do now with three children? Four months now I am seeking any compensation from that company office here in Manila, they are saying you must get a lawyer … How can I afford a lawyer … we need help but no one listens to us." (translated from Tagalog)

3.4 Filipino Bosun — leg amputated in Djibouti. Interviewed Manila, May 2025

"As you see, I cannot work at sea or anywhere anymore … I cannot even feed my family. The Government is not helping me; I spent a large sum of money on lawyers and they say it will take time to get me compensation."

3.5 Filipino 3rd Officer — Manila, May 2025

> *"My family invested a lot for me to complete my maritime education; I was happy to join as an officer in this company which was not paying very good salaries, but I said to myself: it is a start … then they told us after one month that we are going to pass through the Red Sea as using the Suez Canal is more economic than turning around Africa. The rumours were that ships were being bombarded in the*

southern Red Sea — I was having nightmares every night. When we protested, the company said you can disembark if you don't like it … I chose to leave in China and pay for my own ticket back home to Manila. I don't need this extra stress in my life … I lost a lot of money … but I am still in one piece."

3.6 Greek Chief Officer — outer anchorage, Jebel Ali, March 2026

"Now we are stuck here with our cargo. I was supposed to end my tour of duty and disembark in Europoort this month. Now we are so stressed … no one is answering our questions. Airports here seem to be unsafe also, but the company is not talking to us. Our last month's salaries did not reach our accounts. We are running out of credit here at the outer anchorage and not able most of the time to call home. My wife is pregnant and due to deliver soon … I don't know whether my baby arrived or not. Even our food supplies are running low and the ship chandler says he needs a green light from the company before getting us supplies out there."

3.7 VLCC Captain — outer anchorage, Fujairah, March 2026

"I don't know what to say … this war here seems to be intensifying; we were supposed to enter the Fujairah terminal a week ago to load our cargo. The terminal kept postponing our docking time. Yesterday, we could see that the tank farm area in Fujairah was on fire — they say Iranians hit it. So how can I guarantee the safety of my crew now if we go in the terminal to load? Everyone is so stressed and they want to go home. I cannot run the ship like this; this is not what we signed for."

3.8 Thai Second Engineer — hospital, Ras Al Khaimah, March 2026

"I never imagined in my life that my ship would get hit by a missile. We were sailing out of the Gulf then we heard a large bang in the engine control room. We called the bridge — they said we are hit and see smoke and flames from the aft side of the ship. Fire alarms located the steering gear room. We ran there to deal with the fire but saw the whole steering gear on fire and water flooding the room rapidly … we could not deal with that as the hull was breached barely above the waterline. Ten minutes later the Captain sounded the abandon ship alarm and we evacuated the ship in the lifeboats."

4. Data Analysis The Road Map Ahead

The data set, collected over more than two years across several ports and conflict situations, shows that a new type of pressure is being placed on this nomadic global workforce. The seafarers' accounts above represent a selective sample only. The wider interview material shows several repetitive themes: feelings of fear upon entering a known conflict or risky area; shock after attack and uncertainty about support; and a dominant sense among many seafarers that they are left alone once the incident is no longer headline news. This is consistent with recent work on seafarer isolation, welfare and employer responsibility during prolonged disruption (ITF Seafarers' Trust, 2023; Sampson & Ellis, 2023; Carrera-Arce et al., 2022).

4.1 Systematic Thematic Matrix

Table 1 maps the seven core themes identified in NVivo against rank cluster. Frequencies are reported as the number of participants (out of n = 47) whose transcripts were coded under each theme.

Table 1. Distribution of themes across participant clusters (NVivo coding, n = 47).

Theme	Senior Officers (n=14)	Junior Officers (n=11)	Ratings (n=15)	Families (n=7)
Shock and disbelief (acute stress)	14	11	15	7
Stress-related symptoms (sleep loss, intrusive thoughts, hypervigilance)	13	11	15	6
Ambivalence about compensation pathways	6	7	14	7
Fear of job loss / financial precarity	4	10	14	5
Onboard interpersonal tension / multi-national feuds	9	8	11	0
Diaspora, isolation and loss of contact with family	12	10	13	7
Self-blame and regret for accepting the voyage	2	6	11	1

4.2 Cross-Cutting Observations

Ratings and junior officers carried the heaviest burden of financial precarity and self-blame, linked to recruitment fees, debts and family investment in maritime education. Most felt they had less room to refuse a voyage to a war zone, less power to question a company instruction, and fewer savings to protect them if they walked away. Senior ranks Masters and Chief Officers more often reported moral injury: feeling responsible for crew welfare while lacking authority to repatriate distressed seafarers or obtain clear guidance on war-risk cover. Filipino and Indian seafarers reported intensified family-side stress from remittance dependency, visible strongly in Manila interviews. Greek and Thai officers in the 2026 Hormuz cohort spoke more about communication blackouts, delayed salaries and insurance uncertainty. Multiple respondents proposed conflict-awareness training beginning at cadet level in MET institutions, continuing through company familiarisation and pre-departure briefings. Most respondents understood that shipping is regulated by the IMO and ILO but demanded that legal rights particularly MLC standards, war clauses and repatriation rights be made more visible and more enforceable.

5. Understanding Mental Health Challenges

Mental health is seldom discussed openly at sea. Many seafarers still feel it is private, or shameful, or something that may affect their next contract (Sampson & Ellis, 2023). The accounts of interviewees evacuated from damaged ships show shock, disbelief and clear signs of severe stress consistent with post-traumatic stress responses, including intrusive memories, sleep disturbance and hyperarousal. In the documented case of the evacuated Thai tanker crew, formal PTSD diagnoses were issued by attending medical staff at Ras Al Khaimah hospital. Communication with home is a major part of the mental-health issue: a seafarer at the outer anchorage who cannot call a pregnant wife, confirm salary payment, or tell the family when he will return home, is not simply "waiting orders" he is carrying a private emergency while still expected to work professionally (Oldenburg & Jensen, 2019).

Training programmes on conflict awareness can also help multinational crews when the unexpected happens. This study found several cases where onboard tension increased because crew members held different views on the conflict itself in a war-risk area, a divided crew is a safety problem (Zhao et al., 2020). Emergency evacuation preparation for hostilities is not the same as mandatory fire and abandon-ship drills under STCW. Conflict-zone training must go further, covering calm communication under attack, damage control after blast or missile strike, trauma awareness, casualty handling, family notification protocols and post-incident support. These situations are no longer rare enough to ignore.

6. Insurance, Compensation and Future Developments in Maritime Law

Marine insurance contractual agreements are not simple. Most seafarers do not read the full terms of a policy negotiated between the shipowner and the P&I club; even senior officers may understand only the broad outline. Commentary from the IGPI (2024) and JWC (2024) confirms how quickly war-risk listings change in conflict zones and how exclusions are raised earlier in the incident timeline than in past decades. Since the eruption of the Gulf war on 28 February 2026, several major insurance providers declared policies null and void where vessels sail in or near a conflict zone. This leaves Captains unable to answer basic crew questions: if we are hit, who pays? If I am injured, who looks after my family? If the ship is abandoned, how do we get home? Those questions are no longer rhetorical they affect discipline, confidence and safe operation.

Injured seafarers interviewed in the Philippines were unsure where to access compensation after repatriation. Trauma, mental stress and post-traumatic symptoms are difficult to record and prove. Families face months of bureaucracy certificates, employment records, medical reports, legal documents, proof of dependency and, sometimes, legal representation they cannot afford. Concrete pathways proposed here include: (i) a binding amendment to the MLC (2006, as amended) introducing a defined 'conflict-zone welfare standard' covering compensation, repatriation and mental-health follow-up; (ii) an industry-funded Seafarers' Conflict-Zone Fund co-administered by the IGPI, ITF Seafarers' Trust and IMO; and (iii) standardised IMO/ILO templates for documenting stress-related injury for compensation purposes.

Changing maritime law is a slow process. More immediate progress may come from convincing shipowners that crew mental welfare directly affects vessel safety and operational efficiency. Useful alliances have been built before: shipowners, P&I clubs and the ITF have reached practical results on minimum wages, contractual authenticity and certification standards. Similar cooperation is possible for conflict-zone welfare. For building mental fortitude, flag States, shipowners and global and local trade unions must all contribute.

7. Conclusion and Recommendations

The data reveals seven overlapping themes: shock and disbelief; stress-related symptoms; ambivalence about compensation; fear of job loss; onboard interpersonal tension; diaspora and isolation; and self-blame. A rating could feel fear, self-blame and financial pressure simultaneously; a Master could feel anger at the company, worry for the crew and guilt over an injury he could not prevent; a widow could feel grief and still be forced to argue about documents. The global harmonisation of MET creates a rare opportunity to integrate stress-mitigation and conflict-awareness training consistently across countries.

The accounts of seafarers stranded on either side of the Hormuz Strait in March 2026 show multiple simultaneous struggles: within themselves (should I stay or go home?), with the company (where is my salary? what are the orders?), and with their families ashore (worry, pressure and silence). A mental-fortitude training programme would not remove the danger, but it would give crews and officers tools to manage pressure before it breaks discipline or judgement.

Specific Implementation Steps

- A new STCW model course on "Operating in High-Risk and Conflict Areas" covering stress recognition, communication discipline, evacuation under hostile fire and post-incident support.
- A mandatory pre-departure mental-health briefing for all crews entering JWC-listed areas (JWC, 2024), logged in the ship's official logbook and providing a documented option for seafarers to withdraw.
- Embedding ISWAN's Seafarer Help Line and equivalent national services in on-signing safety familiarisation (ISWAN, 2024) in clear and simple language, not small print.
- Encouraging flag States to publish quarterly anonymised statistics on seafarer casualties and stress-related medical disembarkations in conflict zones.

These actions use structures already present: STCW, MLC standards, ITF CBAs, P&I clubs, flag State reporting procedures to the IMO and the GISIS database, company familiarisation and welfare networks. What is vitally needed is to connect them properly to the real conditions now faced by crews in the Red Sea, Black Sea, Gulf and other unstable waters.

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Key Competences for Sustainable Maritime Entrepreneurship

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Abstract: The accelerated implementation of international and European regulatory frameworks for reducing greenhouse gas emissions in shipping, along with the EU's goal of climate neutrality by 2050 and commitments to the UN Sustainable Development Goals, is reshaping the maritime sector. These developments impose new operational and behavioural requirements, highlighting the growing importance of sustainable maritime entrepreneurship as a driver of innovation and compliance. The study aims to identify and systematise a set of environmental, regulatory, digital and managerial competences that maritime universities should develop in future professionals. The objective is to support the effective implementation of sustainable and innovative solutions in real operational environments. Two main methods are applied. First, an analysis of key international and European strategic documents is conducted to determine the required knowledge and skills for managing environmental and operational challenges. Second, a survey using Likert scales is carried out among maritime sector managers to assess current competency levels and training needs. The findings highlight four key groups of competences: environmental and energy, regulatory, digital and analytical, managerial and transversal. The study emphasises the critical role of these competences for sustainable maritime entrepreneurship and recommends integrated training approaches – such as simulations, case studies and expert input – to enhance the practical applicability of maritime education.

Keywords: key competences; sustainable maritime entrepreneurship; regulatory compliance; digital competences; sustainable management

1. Introduction

Maritime transport is among the most energy-efficient modes of transport; however, at the same time, it constitutes a significant and increasing source of greenhouse gas emissions. In 2018, emissions from maritime shipping amounted to 1,076 million tonnes of CO_2, accounting for approximately 2.9% of total global emissions generated by human activity. Projections indicate that, by 2050 these emissions may increase by up to 130% compared with 2008 levels, which would be inconsistent with the priorities of the Paris Agreement aimed at preventing dangerous climate change through limiting global warming. Statistical data indicate that the European Union's contribution to total CO_2 emissions amounts to approximately 3–4%, corresponding to more than 124 million tonnes of CO_2 in 2021 (European Commission n.d.). Achieving a substantial reduction in greenhouse gas emissions from international shipping requires the implementation of global measures. The effectiveness of such measures depends directly on the availability of qualified specialists with appropriate environmental, technological and managerial competences, capable of implementing these measures efficiently, using the most appropriate methods, in both maritime theory and practice.

This paper aims to identify and systematise an integrated set of environmental, regulatory, digital and managerial competences that should be developed by maritime universities in future maritime transport specialists. Particular attention is given to the effective implementation of innovative technologies, tools and methods that support the achievement of sustainable development principles in real operational environments.

To achieve the stated aim, this research addresses the following key objectives:

- to examine and analyse key international and European strategic documents, together with relevant specialised literature, in order to identify the core knowledge and competences required for the implementation of sustainable maritime practices and innovations;

- to conduct a pilot empirical study of these key competences and, based on the findings, to propose recommendations for the effective education and training of future maritime professionals.

In line with research objectives, the study is subject to certain limitations and challenges, which can be summarized as follows

1. Theoretical limitations - The topic of sustainable maritime innovation is highly dynamic, with knowledge in this field evolving rapidly. As a result, the academic literature reflects ongoing debates regarding the scope and dimensions of sustainable entrepreneurship (Kamaludin et al., 2024; Lumpkin et al., 2018). These discussions largely stem from the absence of universally accepted principles and criteria, particularly in relation to the contributions of sustainable innovations to the development of maritime companies of varying sizes, regional prosperity and broader societal well-being.

2. Empirical limitations - The study is at a pilot stage of development. A subsequent full-scale empirical investigation is expected to provide a more substantial contribution to understanding the application and role of experimental approaches in fostering entrepreneurship and sustainable innovation within the maritime sector.

- The analyses and interpretations of the findings are valid for Bulgarian maritime organisations. They reflect the level of innovation activity within the sector, as well as the characteristics of the organizational and national innovation culture during the study period (2022-2025).
- The generalizability of the findings to other sectors or countries is limited due to the specific characteristics of the maritime industry in each national context, including differences in technological capabilities, regulatory frameworks, and innovation cultures, as well as the dynamic nature of contemporary maritime challenges.

3. Organisational and methodological limitations - The limitations are associated with the sampling process of the questionnaire survey. They relate to practical organizational constraints, including the availability of time, the research setting, and financial, human, and technological resources required to achieve the objectives and implement the empirical study.

2. Relevance of the study

The implementation of new regulatory requirements is strongly dependent on the advancement of sustainable maritime entrepreneurship, which functions as a linking mechanism between the regulatory framework, technological innovation and human capital development within the sector. In the context of increasingly stringent environmental standards and decarbonisation policies, entrepreneurial initiatives in the maritime industry not only respond to regulatory demands but actively transform them into drivers of innovation and competitiveness (Orosa, 2023).

On the one hand, sustainable maritime entrepreneurship facilitates practical compliance with regulatory requirements through the development and implementation of innovative technological solutions, including alternative fuels, energy-efficient systems, the digitalisation of operations and intelligent emission monitoring systems (Grosso et al., 2021). In this way, regulations are transformed from administrative obligations into economic opportunities for the creation of new markets and services.

On the other hand, this process is inherently linked to the need to adapt the education and training of maritime professionals (SkillSea Project, 2022; Atanasova 2024; Alexiev and Narlev, 2025). The emerging requirements (European Union 2025) necessitate the acquisition of knowledge and competences in areas such as carbon emission management, the use of alternative energy sources, digital technologies and the sustainable management of ship operations. In this context, maritime entrepreneurship acts as a key driver for the development of educational programmes, public–private partnerships and training platforms that equip specialists with the competences required to effectively implement the new regulatory framework.

The interaction between regulation, entrepreneurship and education creates an integrated approach to the sustainable transformation of the maritime sector. Alongside the implementation of innovations, entrepreneurial structures generate demand for new types of competences, which in turn leads to the modernisation of education and the upskilling of maritime professionals. In this way, sustainable maritime entrepreneurship emerges as a strategic factor for the accelerated and effective implementation of regulatory requirements, as well as for the long-term development of the sector.

An examination of these dimensions, together with the relevant academic literature, indicates that sustainable entrepreneurship plays a key role in promoting supply chains through its economic, environmental and social contributions (Stefanova and Kanev, 2022). Cooperation and integration among entrepreneurs and various stakeholders, including local communities, public institutions and the non-profit sector, are essential for achieving long-term sustainability objectives in the maritime industry.

By its nature, sustainable entrepreneurship represents both a process and an outcome of triple optimisation, commonly conceptualised as the Triple Bottom Line model, which is grounded in social, environmental and economic sustainability. This approach aims to achieve financial stability, social welfare and environmental responsibility simultaneously, thereby generating benefits for organisations, society and the natural environment (Nicholls, 2018). Within the scope of this study, sustainable entrepreneurship is defined as a set of maritime business practices aimed at identifying and implementing innovative strategies for the development of contemporary sustainable approaches, principles and frameworks for generating social, environmental and economic innovations.

3. Methodology of the Study

To achieve the stated research objective, a combined research approach was adopted, integrating document analyses and an empirical study based on a questionnaire survey. The first method involves the analysis of key international and European strategic documents (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), International Convention for the Prevention of Pollution from Ships (MARPOL), IMO GHG Strategy (IMO, n.d.c), European Green Deal, FuelEU Maritime (Regulation EU 2023/1805), The EU Emissions Trading System (EU ETS)), together with the specialized reference Global Maritime Professional Body of Knowledge (IAMU, 2019), to identify the knowledge and competences required for the development and implementation of sustainable maritime practices and innovations. The second method is based on a survey conducted among managers within the maritime sector of the Republic of Bulgaria, aimed at assessing the level of preparedness and the actual competences of maritime professionals regarding the effective adoption of innovative technologies, tools, and methods for achieving sustainable maritime innovation.

To achieve the research objectives, initial selection criteria for maritime organisations were defined as follows: 1|) The study includes companies that had reached the “maturity” stage of their organizational development at the time of survey; 2) The participants in the survey were managers holding positions at senior or middle management levels within the organizational hierarchy.

Based on the defined selection criteria, a systematic non-representative sample including 45 companies was established. The empirical study was based on the responses provided by managers representing 40 companies with extensive experience in the maritime sector of the Republic of Bulgaria. Specifically, the selected companies are considered to play a strategic role in the sustainable management of supply chains due to their potential to implement green entrepreneurship practices, participate in the circular economy, and promote corporate social responsibility initiatives. The pilot empirical study was conducted over a three-year period (2022-2025). The survey instrument is a questionnaire consisting of sections covering variables related to key competences for sustainable maritime entrepreneurship and variables measuring the innovation climate within maritime organisations. The survey responses were measured using a five-point Likert scale, ranging from 1 (“strongly disagree”) to 5 (“strongly agree”). The survey identifies management attitudes towards sustainable entrepreneurship and the mechanism for stimulating entrepreneurial activity in maritime companies. The questions included in the study also addressed the role of management and intrapreneurs in shaping sustainable maritime practices, along with the key challenges and barriers to innovation within the maritime sector. Statistical analysis of the relationships between the examined variables was carried out using the XLSTAT 2024 software package.

3.1. First Method

In the maritime sector, an accelerated adoption of international and European legal frameworks aimed at the reduction and elimination of greenhouse gas (GHG) emissions is being observed, marking a transition from voluntary practices to mandatory global and regional requirements (IMO n.d.a; Sustainable Ships n.d.). The International Maritime Organisation (IMO) and the European Union (EU) are the primary driving forces in this process, with the objective of achieving net-zero emissions by around 2050, supported by significant interim targets for 2030 and 2040 (Jao and Alvi, 2026).

In recent years, as a result of increasing decarbonisation pressure, several key regulatory initiatives have been introduced, requiring (IMO 2025; Finnish Government, 2025):

- the accelerated implementation of measures and technological solutions, including the IMO Net-Zero Framework (under development), the EU Emissions Trading System (EU ETS), the inclusion of methane and nitrous oxide emissions, the FuelEU Maritime Regulation (2025) and operational energy efficiency measures (CII);
- the acceleration of compliance processes and the deployment of relevant technologies, such as a global fuel standard, economic measures, onshore power supply (OPS) and green shipping corridors.

Among the principal international and European instruments introducing sustainability requirements in the maritime sector are the International Maritime Organisation's MARPOL Convention, the EU's "Fit for 55" package (including the FuelEU Maritime Regulation and the EU Emissions Trading System (EU ETS), as well as the Corporate Sustainability Reporting Directive (CSRD) (Diamantara, 2025). These frameworks aim to reduce the intensity of greenhouse gas emissions, the use of low-carbon fuels, the deployment of shore-side electricity (also referred to as cold ironing) and the establishment of stringent requirements for monitoring, reporting and verification of environmental performance indicators (European Union, n.d.).

Primary importance is attributed to the international instruments and conventions adopted under the framework of the IMO, including:

- the MARPOL Convention, which establishes global standards for the prevention of pollution from ships, covering oil pollution, sewage, garbage and atmospheric emissions arising from maritime operations;
- the IMO GHG Strategy, which sets ambitious targets for reducing greenhouse gas emissions from international shipping, with the objective of achieving net-zero emissions by around or before 2050;
- the Ballast Water Management Convention (2004), which requires the control and management of ballast water and sediments in order to prevent the spread of harmful aquatic organisms and pathogens;
- the AFS Convention (International Convention on the Control of Harmful Anti-Fouling Systems on Ships, 2001), which regulates the use of anti-fouling coatings on ships with the aim of limiting their adverse impact on the marine environment.

Several EU regulations and directives further contribute to advancing sustainable development in the maritime sector, including:

- the FuelEU Maritime Regulation (Regulation (EU) 2023/1805), which introduces a gradual reduction in the greenhouse gas intensity of energy used on board ships, targeting up to an 80% reduction by 2050, as well as the mandatory use of OPS for ships at berth from 2030;
- the EU ETS Maritime (Emissions Trading System), under which, from 2024, shipping companies are required to monitor, report and surrender allowances for CO_2 emissions from voyages involving EU ports;
- the EU MRV Regulation (Monitoring, Reporting and Verification), which obliges shipowners to monitor and report CO_2 emissions, fuel consumption and cargo-related data for ships above 5,000 gross tonnage;
- the CSRD, which requires companies, including large shipping operators, to disclose sustainability-related information in accordance with the European Sustainability Reporting Standards;
- the EU Ship Recycling Regulation, which establishes requirements for the safe and environmentally sound recycling of ships at the end of their operational life;
- the Revised Directive on Ship-Source Pollution, which strengthens measures to prevent illegal discharges from ships and aligns EU legislation with the requirements of MARPOL.

The main areas of knowledge, skills and competences required for the development of modern maritime professionals are defined in the specialized international reference document Global Maritime Professional Body of Knowledge (GMP-BoK) (GMP-BoK, 2019). This document aims to support maritime universities in updating their curricula and achieving educational outcomes aligned with the changing needs of the maritime industry. Its focus on the adaptive capacity of maritime professionals makes it a conceptual foundation for identifying the knowledge and capabilities required by future maritime workforce to achieve a sustainable transition of the maritime sector. In this context, the BoK is considered a linking element in the transition from a training model focused on the professional performance of specific tasks towards an integrated model for the

development of key competences, entrepreneurial capabilities, and an orientation towards sustainable innovation.

The mechanism through which the transition from operational optimisation to technological innovation and strategic, long-term decision-making is realised is sustainable maritime entrepreneurship, which requires the acquisition of specialised knowledge and targeted training across several key domains (IMO, 2023):

1. Actions and behaviour – maritime professionals are required to integrate energy efficiency into daily operations, including the optimisation of maritime processes, the maintenance of systems, energy management, compliance with regulatory requirements, data collection and performance reporting, and the use of emerging technologies. The transition to alternative fuels (such as hydrogen, ammonia and biofuels) necessitates new operational procedures compared to conventional fossil fuels, as well as the management of deficits and the use of "compensatory units" within the Net-Zero framework.

2. Required knowledge – professionals must possess a combination of technical, regulatory and safety-related knowledge to support maritime decarbonisation. This includes an understanding of alternative fuels and their associated risks, life-cycle assessment and emissions accounting, as well as familiarity with the regulatory framework and the IMO's decarbonisation targets. They must also be familiar with emerging technologies and capable of monitoring operational performance to ensure compliance and operational safety (Steamship Mutual, 2022).

3. Education and training requirements – projections indicate that by 2030 the maritime sector will face a shortage of qualified personnel. Consequently, training must be formalised and targeted. Core competence areas should include fuel storage and handling, as well as emergency response. Capacity-building initiatives and training standards (IMO, n.d.a; IMO, n.d.b) and the development of specialised courses within academic institutions (IMO 2023, Lutzkanova et al. 2024) are essential for addressing these needs.

4. Certification – professionals will be required to obtain updated certificates of competency or endorsements aligned with the forthcoming amendments to the STCW Convention.

In summary, the findings derived from the first method confirm that the transformation of the maritime sector at both regional and global levels is driving new and innovative directions in the development of regulatory and normative maritime frameworks. These developments are closely linked to the enhancement of innovation-related competences within the maritime sector, contributing to the resolution of significant social, economic and environmental challenges in the maritime industry at the local, national, and global levels.

3.2. Second Method

The implementation of sustainable maritime innovations is a crucial step in building and managing sustainable supply chains in the maritime sector. For this reason, research on these innovations contributes to environmental, social, and economic sustainability. The empirical study focuses on the development and implementation of sustainable innovations within maritime companies, particularly positive managerial attitudes and systems designed to stimulate entrepreneurial activity. At the same time, the approach used allows for the identification of problem areas that hinder the implementation of successful sustainable and entrepreneurial practices in Bulgaria.

One of the study's primary objectives is to identify management attitudes toward sustainable entrepreneurship. The results of the survey indicate that 100% of managers demonstrate a positive managerial attitude toward the development of sustainable entrepreneurship in maritime companies (Table 1).

Table 1. Attitudes towards sustainable innovations

		Variable	Percentage	Valid Percentage	Cumulative Percentage
Valid Cases	Yes	40	100	100.0	100.0
Missing Cases		0	0		

The results of the survey, conducted using Likert-scale instruments, reveal managerial attitudes regarding the actual skills and competences of maritime professionals in relation to sustainable maritime innovation. The findings indicate that economic competences are prioritised (35%), followed by environmental competences (33%), while social competences account for only 5% (Figure 1).

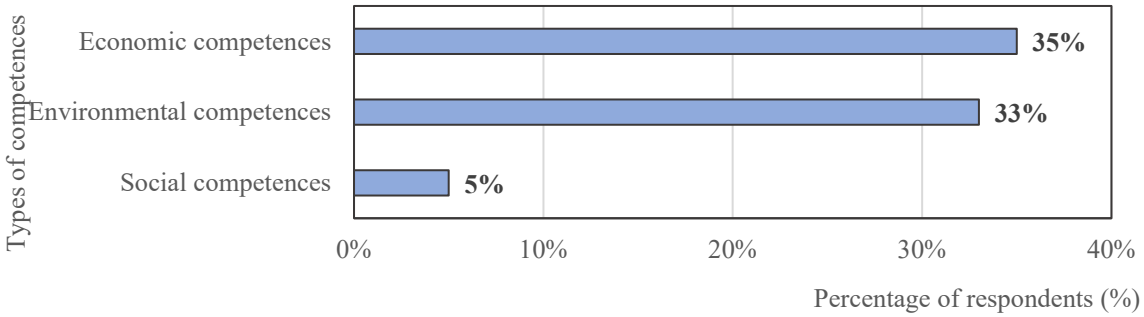


Figure 1. Key Competences for Sustainable Maritime Entrepreneurship

In addition, social competences are ranked lowest in terms of perceived importance, which may be explained by several critical challenges in the maritime sector, including issues related to safety and security, the increasing threats of maritime piracy and the need to standardise fair social practices across the industry at a global level.

The results of the empirical study also identify a further significant challenge related to sustainable maritime innovation. Sectoral issues are associated with a lack of integration between economic, environmental and social competences, as indicated by 76% of the surveyed managers. The underlying reasons include the strong prioritisation of economic factors, reported by 60% of respondents, as well as the mandatory nature of a number of environmental requirements within the maritime sector (55%).

The analysis further demonstrates that additional competences make a significant contribution to the implementation of smart and sustainable maritime innovations. In particular, regulatory competences (33%) are essential for ensuring stricter compliance with international and European requirements, as well as for effective monitoring and reporting. Digital competences (25%) are also significant, reflecting the sector's increasing reliance on data management, digital systems, sustainability indicators and process optimisation.

The pilot study revealed that managers highly value the creation of a favourable environment for developing the core competences of maritime professionals related to innovative maritime entrepreneurship. The highest level of confidence was attributed to the establishment of an integrated system combining educational, organisational, financial, technological, and regulatory mechanisms (95%) in the form of living laboratories, incubators, and accelerators, due to its potential to enable sustainable knowledge transfer for the development and implementation of innovative solutions, thereby enhancing the competitiveness of the maritime sector (Figure 2). The second most significant factor identified by respondents was the digital transformation of the maritime sector (90%), in which the adoption of innovative technologies (such as the Internet of Things, blockchain, and other emerging technologies) creates conditions for the development of new sustainable business models in maritime entrepreneurship. The third-ranked factor was the sustainable regulatory framework (80%), which facilitates the implementation of policies supporting low-carbon practices, alternative fuels, smart ports, and cooperation among governments, industry, and educational institutions.

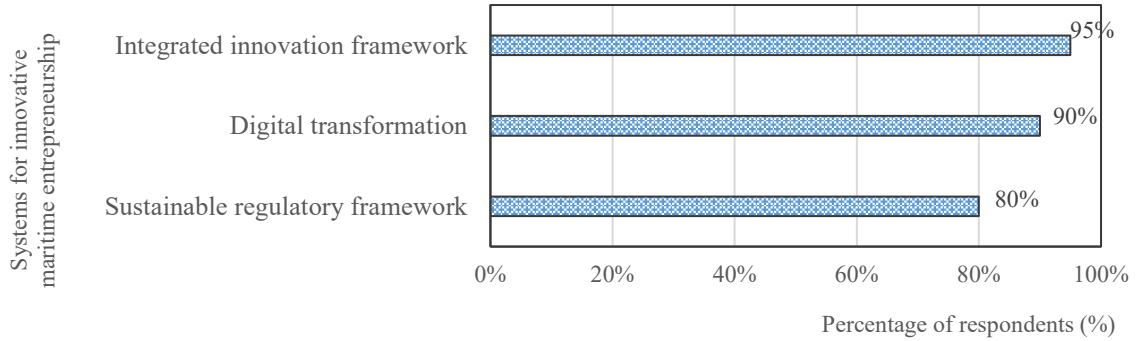


Figure 2. Frameworks for Supporting Innovative Maritime Entrepreneurship

4. Results from the study

The analysis of the results indicates that the key competences of greatest relevance to the sustainable development of the maritime sector can be broadly categorised into economic and managerial competences, as well as environmental and social competences. Digital and regulatory competences perform an important supporting role in this context.

The empirical findings further reveal a number of social challenges associated with sustainable maritime innovation. Priority issues in this regard relate to enhancing safety and security, addressing maritime piracy and the need to standardise fair social practices at a global level. 30% of the surveyed managers believe that more sustainable supply chains can be developed through social entrepreneurial networks based on the strengths and resources of different countries, regions, and communities.

Empirical results confirm the critical role of maritime professionals in the development and implementation of sustainable innovations. These innovations are primarily related to supply chains, particularly with regard to reducing adverse impacts on marine resources, increasing the use of renewable energy sources, the adoption of green shipping technologies, waste recycling, hybrid propulsion systems, and other related factors.

In addition, management representatives acknowledge that the innovative entrepreneurial process requires the establishment of a supportive environment for knowledge transfer, the promotion of creative thinking, and the creation of conditions for applied research and development. They also express their readiness to implement systems for fostering innovative entrepreneurship. The support systems for innovative entrepreneurship, their usefulness, and applicability will be tested in the main phase of the research, and the results will be presented in subsequent publications by the authors.

5. Conclusion

The study identifies and systematises the key competences that are critical for the development of sustainable maritime entrepreneurship and for the education and training of future maritime professionals. The development of these competences within maritime universities is essential for ensuring a workforce capable of applying innovative technologies and methods, ensuring regulatory compliance and delivering sustainable solutions in real operational environments. Furthermore, the study recommends the use of integrated teaching and assessment methods, including simulations, case studies, and expert interviews in order to enhance the practical applicability of training. The study of sustainable maritime innovation represents an innovative approach to examining the role and management practices of sustainable supply chains within the maritime sector as well as to generating novel contributions across environmental, social and economic dimensions. Such innovations warrant examination from multiple perspectives and across different stakeholder groups. In the present study, particular attention is given to the operationalisation of sustainable innovation and entrepreneurship within maritime companies. The applied research approach has highlighted several problematic areas that hinder the effective implementation of sustainable entrepreneurial practices in the Republic of Bulgaria. In line with the identified priorities, this study determines the key factors influencing sustainable social entrepreneurship in the maritime sector of the Republic of Bulgaria, including managerial attitudes, the role of maritime professionals and prevailing social challenges. Furthermore, the findings draw attention to critical issues affecting social and entrepreneurial activity such as security threats, regulatory pressures and the dynamics of the international environment.

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Beyond Standard Operating Procedures: A Framework for Simulation-Based Learning in Marine Engineering

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Abstract: Simulation-Based Learning (SBL) in Maritime Education and Training (MET) lacks a domain-specific pedagogical foundation for marine engineering. Current practices prioritize technical fidelity and checklist-driven assessments derived from navigational SBL. While sufficient for well-structured routines, these approaches fail to prepare Engine Control Room (ECR) teams for ill-structured, asymmetrical socio-technical crises. This study addresses this gap by developing a foundational framework for higher education engineering SBL. Employing conceptual theory synthesis, the paper integrates Experiential Learning Theory, Reflective Practice, and Expansive Learning Theory together, with learning transitions regulated by Cognitive Load Theory. The resulting three-tier framework reconceptualizes the simulator from a mere technological replica into a mediating educational tool. It provides instructional designers with a structured pathway to escalate scenarios from individual routine automation (Standard Operating Procedures) to dynamic diagnostic reasoning, and ultimately to distributed team cognition under extreme operational pressure. By establishing a robust, domain-specific pedagogical model, this study elevates engineering SBL from mechanical execution to collaborative socio-technical problem-solving.

Keywords: Maritime Education and Training, Simulation-Based Learning, Expansive Learning, Experiential Learning

1. Introduction

Modern commercial vessel Engine Control Rooms (ECRs) are complex socio-technical systems. Marine engineering officers are required not only to maintain traditional mechanical reliability but also to operate highly automated processes under continuous pressure. According to Tusher et al. (2024), successful teamwork in such environments demands interpersonal interdependence and coordination mechanisms, including shared mental models, mutual trust, and closed-loop communication. While communication acts as a critical safety link during abnormal situations, increasing automation introduces new challenges. The current literature on the effects of automation on team coordination remains somewhat contradictory, highlighting the urgent need for further research specifically tailored to the socio-technical training of engine room teams (Tusher et al., 2024).

To meet the maritime industry's standards of training and certification for engineering officers, such as those mandated by the STCW convention, Simulation-Based Learning (SBL) has long played a central and expanding role in Maritime Education and Training (MET). However, while the technological fidelity of engine room simulators has advanced exponentially to replicate complex systems, the pedagogical frameworks guiding socio-technical training have not evolved at the same pace.

Current SBL practices in marine engineering rely heavily on didactic models developed for bridge navigation, which in turn were adapted from aviation Crew Resource Management (CRM) concepts. These inherited models are designed for environments where the development of situational awareness is largely linear, problems are spatially oriented, and challenges are externally observable. Conversely, in ECR and process control, operations and anomalies are internal, latent, and non-linear. Consequently, marine engineering SBL lacks distinct, domain-specific pedagogical guidelines.

As a result of this pedagogical vacuum, the design and assessment of ECR simulation exercises frequently default to technical execution and the mechanical adherence to Standard Operating Procedures (SOPs). This

phenomenon is maintained by the International Maritime Organization's (IMO) Model Course 2.07 (International Maritime Organization, 2017). Although the model course is a vital global standard for achieving STCW competencies, its didactic structure and assessment criteria rely heavily on a behavioristic, performance-centric paradigm. The assessment of competence is practically bound to procedure-specific checklists, prioritizing numerically measurable and externally observable actions (e.g., opening a specific valve or starting pumps in sequence). Consequently, instructors are inadvertently guided toward a 'tick-box' method of assessment.

While this approach is justified for securing safety-critical routines (well-structured problems), it fails to provide instructors with adequate pedagogical tools to guide cognitive processes, diagnostic reasoning, or shared situational awareness. The management of a complex socio-technical system is thus problematically reduced to a mechanical chain of isolated, linear procedures.

Mastery of routines is essential, but it only represents the solving of well-structured problems. When an unexpected, asymmetrical disturbance occurs, such as a blackout in a restricted waterway, the operational challenges immediately become ill-structured. While modern high-fidelity simulators are highly capable of facilitating training for such crises, resolving ill-structured problems requires dynamic diagnostic reasoning and the ability to collectively generate new solutions as a team. Current SBL frameworks fail to adequately explain or guide this transition from mechanical routines to holistic, socio-technical troubleshooting. To address this gap, this study asks the following research question: *What are the essential aspects of a foundational framework for higher education marine engineering SBL?*

The objective of this study was to formulate a conceptual framework that elevates the design of simulation exercises from mere technical execution to a multidimensional socio-technical activity. Through theory synthesis, this paper integrates three previously distinct theoretical lenses: Experiential Learning Theory, Reflective Practice, and Expansive Learning Theory. By utilizing Cognitive Load Theory as the regulating mechanism, the resulting framework re-conceptualizes the simulator: it is no longer viewed merely as a technical replica of reality, but as a mediating tool for learning by collaborative action.

2. Methods

The methodological approach applied in this study is conceptual theory synthesis. The objective of theory synthesis is to achieve integration across multiple theories, concepts, or literature streams, thereby creating a new, higher-order perspective of the phenomenon under investigation (Jaakkola, 2020). This method is highly justified in contexts such as marine engineering simulation pedagogy, where the knowledge describing the research subject is fragmented across various disciplines and heavily reliant on frameworks borrowed from other fields.

To successfully execute the theory synthesis, the foundational building blocks of the phenomenon needed to be identified. A literature review was conducted to map the current state of simulation pedagogy in marine engineering and related technical training. The literature search was executed across three major scientific databases: Scopus, Web of Science, and EBSCO. Search strategies were constructed around four intersecting themes: simulation technologies and immersive environments; pedagogical and didactic approaches; cognitive processes and the development of expertise; and dynamic technical operational environments.

The searches were iterative and deliberately limited to engineering, process control, and maritime operations. Medical and healthcare simulation studies were explicitly excluded, as their clinical and patient-safety-centric learning environments differ structurally from the asymmetrical socio-technical problem-solving required in engine rooms. The selected dataset served as an analytical tool to categorise the pedagogical requirements and shortcomings of ECR simulations. A thematic analysis of the literature confirmed that marine engineering SBL continues to rely on models copied from navigation and on mechanical execution. A cohesive model for ill-structured problems and team-level dynamics was absent.

The identified pedagogical gaps and requirements were distilled into three distinct but hierarchical categories: 1) Challenges in mastering mechanical routines and Standard Operating Procedures (SOPs), which demand repetition and concreteness. 2) A lack of dynamic and situation-bound reasoning (troubleshooting), where mere adherence to rules is insufficient for resolving anomalies. 3) The breakdown of shared cognition and teamwork during asymmetrical crises, where the socio-technical system becomes overloaded.

As Jaakkola (2020) posits, theory synthesis is not merely about identifying research gaps, but a methodological process that transforms prevailing understanding by uniting previously isolated perspectives. Therefore, to directly address the three identified categories, the conceptual building blocks were selected: Experiential Learning Theory (Kolb, 1984) to explain the acquisition of baseline routines; Reflective Practice (Schön, 1983) to support diagnostic troubleshooting; and Expansive Learning Theory (Engeström, 1987) as the solution for team dynamics. By integrating these three lenses via Cognitive Load Theory (CLT), this study constructs a unified framework that directly responds to the pedagogical deficits identified in the review.

While the literature review identified the pedagogical gaps, the actual theory synthesis was conducted by mapping the evolving stages of ECR problem typology (well-structured, ill-structured, asymmetrical) against the cognitive demands of the learners. Cognitive Load Theory (CLT) was employed as the overarching regulatory mechanism to synthesize Experiential Learning Theory, Reflective Practice, and Expansive Learning Theory into a single, sequential framework. This integration shifts the focus from managing individual working memory during routine tasks to facilitating distributed cognition during systemic breakdowns.

3. Theoretical Background

Research on the effectiveness of SBL is well-established, particularly in aviation and healthcare, guided by high-quality meta-analyses (Chernikova et al., 2020) and comprehensive bibliometric reviews (Hallinger & Wang, 2020). SBL research suffers from a recognized 'balkanization' of knowledge across different disciplines (Hallinger & Wang, 2020), a phenomenon that has left domain-specific pedagogy for marine engineering (ERM) significantly underdeveloped.

A common conceptual trap in MET SBL is conflating the device with the educational event. A simulator is merely a physical or virtual apparatus, whereas simulation is the pedagogical technique that utilizes this apparatus to construct experience (Fritz et al., 2008, cited in Hopwood et al., 2016). Relying solely on the simulator frequently traps educational design in a technological 'mirror logic' (Hopwood et al., 2016), failing to recognize the socio-technical complexity of the actual learning activity. Furthermore, simulation is a social practice bound to time, space, and context, where humans interact purposefully with each other and cultural artefacts (Dieckmann et al., 2007, cited in Battista, 2015). As Battista (2015) demonstrates, analyzing these interactions through the lenses of assigned roles and available tools reveals the true socio-cognitive complexity of the simulation environment.

In ECR training, relying solely on technological fidelity is insufficient; the true educational value lies in the simulation's capacity to facilitate deep conceptual understanding and dynamic decision-making. Because current ECR simulations often lack this nuanced pedagogical foundation, they default to low-level troubleshooting and the mechanical repetition of SOPs borrowed from bridge or aviation models, failing to prepare experts for the latent, non-linear, and asymmetrical anomalies inherent to modern engine rooms.

Cognitive Load and Problem Typology

To manage the complexity of a socio-technical system, simulation pedagogy must support higher-order cognitive processes. In ECR operations, where a single fault instantly cascades into dozens of variable changes, the capacity to understand cause-and-effect relationships is vital. According to Cognitive Load Theory (CLT), managing this complexity demands the organization of information into cognitive schemas within long-term memory, thereby preventing the rapid overload of limited working memory (Sweller, 1988). Furthermore, as Choi et al. (2014) demonstrate, the physical learning environment itself acts as a distinct causal factor of cognitive load. In high-fidelity ECR simulations, environmental stimuli such as continuous engine background noise, sudden auditory alarms, and visual lighting changes impose an additional extraneous load on the learners' working memory. This makes the automation of foundational routines even more critical, as the physical simulation environment constantly competes for the students' limited cognitive resources.

The theoretical foundation for this progression stems from Sweller’s (1988) foundational research, which demonstrated that forcing novices into complex problem-solving (e.g., means-ends analysis during an anomaly) consumes their entire working memory capacity. This cognitive overload actively interferes with learning and schema acquisition. Therefore, before learners can effectively troubleshoot ill-structured crises, they must first develop domain-specific cognitive schemas that allow them to process technical information efficiently.

By offering a safe environment, properly designed simulations act as enabling and facilitating tools; they significantly reduce the cognitive load and mental effort required for complex problem-solving (Schnotz and Rasch, 2005, cited in Sauvé et al., 2007). This reduction in extraneous cognitive burden is exactly what allows the learner's working memory to focus on the automation of essential operational routines. However, designing this pedagogical pathway requires understanding how human cognitive architecture dictates the relationship between instructional guidance and problem typology. As Kalyuga, Ayres, Chandler, and Sweller (2003) emphasize, instructional design must dynamically adapt to the learner's evolving expertise. For novices facing well-structured problems (e.g., executing SOPs), explicit external guidance acts as a necessary substitute for missing internal schemas. Yet, as learners acquire and automate these domain-specific schemas, the reliance on external guidance must be faded. If experienced learners are forced to continuously process redundant external instructions, they expend limited working memory capacity cross-referencing them with their pre-existing internal schemas. This paradoxically causes cognitive overload, known as the expertise reversal effect (Kalyuga et al., 2003). Therefore, to advance expertise, the simulation pedagogy must transition from well-structured procedural adherence to ill-structured diagnostic uncertainty.

Addressing ill-structured problems in simulations requires careful instructional scaffolding to avoid cognitive overload. Crucially, as Chernikova et al. (2020) highlight, SBL design must account for the expertise reversal effect (Kalyuga et al., 2003). While deep structural guidance and direct prompts act as essential 'training wheels' for novices, they become intrusive and hinder cognitive freedom as expertise grows. If training relies on pre-scripted, well-structured scenarios, learners cannot apply their knowledge adaptively, and professional competence remains fixated on well-structured resolutions. Similarly, while embedded reflection yields optimal results for experienced learners, it can interrupt the fragile problem-solving processes of novices, leading to cognitive overload (Chernikova et al., 2020). Thus, pedagogy must dynamically adapt to the learner's evolving cognitive architecture.

Theoretical Building Blocks for a New Synthesis

To address these challenges, this study integrates three distinct learning theories to form a cohesive socio-technical framework.

First, Kolb's (1984) Experiential Learning Theory (ELT) is adopted to explain the mastery of baseline routines. ELT provides a structured process where knowledge is created through the transformation of experience. Meta-analyses indicate that experiential pedagogy systematically yields better learning outcomes than traditional methods (Burch et al., 2019). In ECR training, ELT forms the theoretical anchor for internalizing SOPs, transforming passive observation into active conceptualization and experimentation.

Second, to address the transition from automated routines to dynamic troubleshooting, Schön's (1983) theory of Reflective Practice is integrated. Chernikova et al. (2020) identify reflection as the most effective scaffolding mechanism in SBL, particularly for advanced learners. Schön's concept of reflection-in-action is critical here: in modern engine rooms, expertise is not merely the repetition of routines, but the ability to dynamically evaluate and adapt solutions during anomalies where standard procedures are exhausted.

Finally, Engeström's (1987) Expansive Learning Theory acts as the synthesizing force. Traditional models struggle to capture the complexity of teamwork in asymmetrical crises. Expansive learning shifts the analytical focus from individual performance to the collective action of the entire engine room team and the activity system. It provides tools to understand learning in ill-structured situations, where solutions must be collectively created by identifying and resolving internal systemic contradictions.

Within this theory synthesis, the simulator is redefined: it is no longer merely a high-fidelity replica, but a mediating tool that facilitates the transition from structured individual routines to dynamic reflection, and ultimately to expansive, collective problem-solving. It provides tools to understand learning in ill-structured situations, where solutions must be collectively created by identifying and resolving internal systemic contradictions, often manifesting as a 'double bind' where adherence to standard procedures actively conflicts with system survivability.

4. Results: The Socio-Technical Simulation Framework

The primary outcome of this conceptual synthesis is a dynamic, three-tier pedagogical framework designed for marine engineering SBL. The framework illustrates the construction of engineering expertise through three mutually supportive levels. Engeström's (1987) Expansive Learning Theory serves as the overarching meta-theory, conceptualizing the simulator not merely as a technical replica, but as a mediating tool for learning. The transition between these three levels is regulated by Cognitive Load Theory (CLT).

The framework (Figure 1) dictates that pedagogical design must escalate linearly from well-structured individual routines to ill-structured, socio-technical team crises. To demonstrate the practical utility of this framework for instructional designers, its application is explained below using a progressive ECR scenario: *"Pilotage & Power Management Escalation"*.

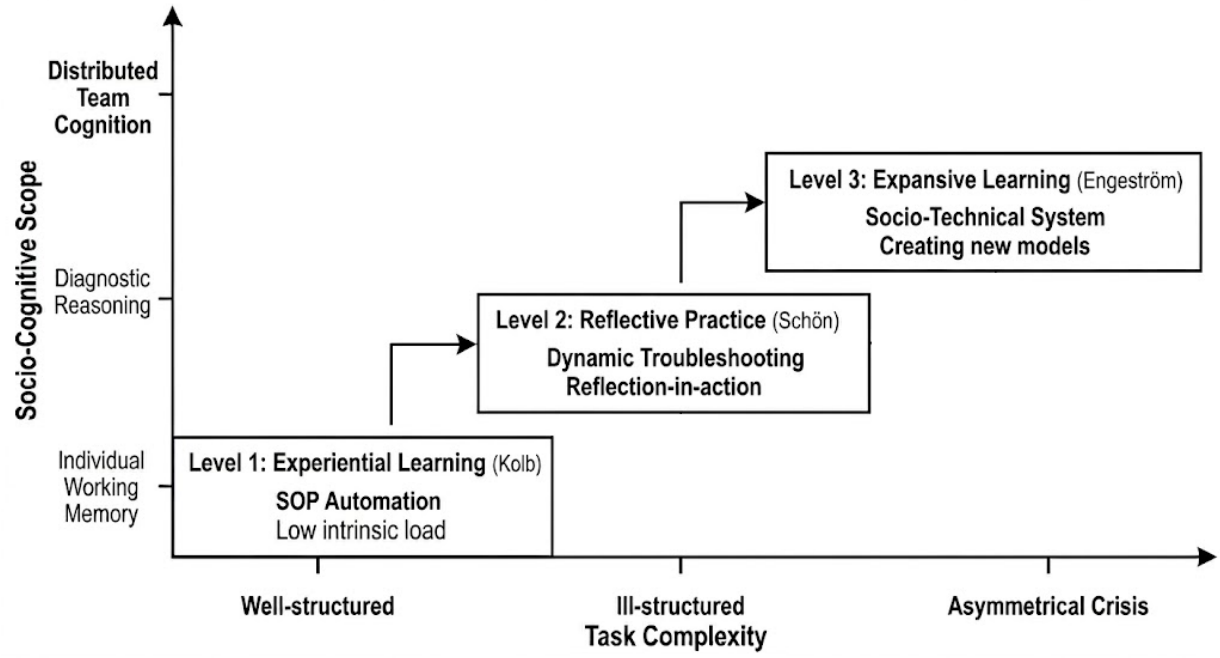


Figure 1. The three-tier socio-technical framework for marine engineering SBL.

Level 1: Experiential Learning and SOP Automation

The foundational level is anchored in Kolb's (1984) Experiential Learning Theory. In the context of STCW (e.g., A-III/2), this level represents the mastery of Standard Operating Procedures (SOPs) and checklists. At this stage, the learner encounters well-structured problems with a single correct solution. From a CLT perspective, the intrinsic cognitive load for a novice is high enough even during basic operations. Therefore, pedagogical design must focus on repetition and clear scaffolding.

The goal is the construction and automation of stable cognitive schemas. This pedagogical choice is strongly supported by meta-analytical data. Chernikova et al. (2020) demonstrated that for learners with low prior knowledge, instructional scaffolds that provide high levels of explicit guidance, such as prompts and step-by-step examples (e.g., SOPs), are statistically the most effective. By reducing task complexity to manageable approximations of practice, these scaffolds prevent cognitive overload during the initial phases of expertise development.

According to Sweller (1988), expertise is largely defined by the possession of domain-specific schemas that enable forward-working reasoning rather than blind search. In this context, SOPs and checklists act similarly to 'worked examples' in cognitive psychology: they eliminate the heavy extraneous cognitive load associated with trial-and-error problem-solving. By following structured procedures, the learner's working memory is freed to focus purely on the construction and automation of stable cognitive schemas regarding the engine plant's baseline functions.

Level 1 example for exercise scenario design: Pilot Arrival Preparations. Task: Execute standard operating procedures (SOPs) to start and synchronize two auxiliary engines ahead of pilot arrival. Pedagogical objective: Automate baseline cognitive schemas via active experimentation (Kolb). The simulation environment is strictly controlled to minimize extraneous cognitive load, providing explicit scaffolding. The instructor acts

as a cognitive gatekeeper: if the learner's working memory is overloaded by baseline synchronization, evidenced by procedural fixation or communication breakdown, the scenario is halted. Successful schema automation is an absolute prerequisite for escalation.

Level 2: Reflective Practice and Dynamic Troubleshooting

The second level shifts the focus from repeating routines to dynamic diagnostic reasoning. The operational necessity of moving beyond routine checklists is empirically evident in modern shipping. As Tusher et al. (2024) demonstrate, advanced ECR automation frequently induces an 'out-of-the-loop' syndrome among operators. Crucially, during sudden automation malfunctions, pre-scripted SOPs are often nonexistent or structurally inadequate, as crises escalate too rapidly for linear checklist adherence (Tusher et al., 2024).

Furthermore, from a cognitive perspective, once routines are automated, merely adhering to checklists can trigger the expertise reversal effect (Kalyuga et al., 2003). Empirical evidence indicates that while strict prompts are highly beneficial for novices, they become detrimental in familiar contexts (Chernikova et al., 2020). As Kalyuga et al. (2003) explain, processing redundant external instructions forces experienced learners to cross-reference them with their already automated internal schemas, paradoxically causing working memory overload. Conversely, reflection phases emerge as the statistically most effective scaffolding mechanism for advanced learners.

Therefore, the simulation's strict SOP scaffolding is deliberately faded, and task difficulty is escalated by introducing ill-structured problems, such as latent system faults. This level relies on Schön's Reflective Practice, specifically reflection-in-action. Because automated routines acquired on Level 1 now occupy less working memory, the learner possesses the germane cognitive resources to reflect on simulator feedback, interpret conflicting data, and perform independent troubleshooting without a pre-scripted resolution. In Cognitive Load Theory terms, the learner has transitioned from a novice relying on heavy instructional scaffolding to an expert utilizing automated schemas. As Sweller (1988) posits, these internal schemas allow the problem-solver to rapidly categorize anomalies and employ forward-working diagnostic strategies, rather than becoming overwhelmed by the multitude of variables changing simultaneously in the ECR.

Level 2 example for exercise scenario design: Latent Anomaly Management. Task: With the baseline stabilized, an exhaust gas temperature deviation occurs on an auxiliary engine, indicating incomplete combustion. Power fluctuates, but the engine does not automatically trip. Pedagogical objective: Transition from rule-based execution to dynamic diagnostic reasoning (Schön's reflection-in-action). The simulation's explicit SOP scaffolding is intentionally faded. Utilizing the cognitive schemas automated in Level 1, the learner must independently interpret latent variables, start a standby engine, and isolate the fault. The simulator is no longer a checklist environment, but an active diagnostic tool requiring forward-working reasoning.

Level 3: Expansive Learning and Socio-Technical Complexity

The highest level of the framework shifts the analytical focus from individual cognition to the socio-technical activity system of the entire ECR. The necessity of this systemic shift is underscored by empirical limitations in current SBL practices. While meta-analyses confirm that simulations yield exceptionally large effects for individual technical performance ($g = 1.06$), their impact on teamwork and collaborative communication remains considerably lower ($g = 0.50$) (Chernikova et al., 2020). This statistical discrepancy highlights the fact that traditional, individually focused simulation models struggle to grasp the extreme complexity of real team dynamics during crises. When a crisis escalates severely, the cognitive capacity of a single watchkeeping officer is inevitably exceeded.

Empirical studies confirm that asymmetrical anomalies, such as automation malfunctions, precipitate an abrupt spike in team 'coordination demand', forcing unplanned reallocations of tasks and rapid shifts in communication networks (Tusher et al., 2024). Managing this systemic overload requires moving beyond individual cognitive models into distributed team cognition. Engeström's Expansive Learning Theory provides the theoretical mechanism for this: learning occurs through the dynamic, emergent interaction of the team, physical tools (automation systems), and social rules (roles, bridge communication). Expansive learning is achieved when the team must collectively resolve systemic contradictions by creating an entirely new, ad-hoc operational model to absorb the sudden coordination demand under extreme pressure.

The pedagogical objective is to forge new operational models under extreme pressure. For instance, the team must decide whether to secure the electrical grid at the expense of bow thruster availability. Furthermore, they may need to completely restructure their roles—such as formally transferring the watch to the chief engineer so the watchkeeping engineer can physically assist the overloaded motorman. They must also consider starting the previously isolated AE1 as a last resort and verifying emergency generator readiness. The scenario is designed so that a single "correct" solution may not exist; the team must collectively aim to minimize catastrophic damage. The simulator transitions into a mediator of the entire socio-technical system, where success relies not on a manual, but on the seamless, emergent interaction of humans, technology, and procedures, the core objective of expansive learning.

Level 3 example for exercise scenario design: Asymmetrical Systemic Crisis. Task: Successive fuel system anomalies cause one generator to trip and another to trigger critical alarms, directly coinciding with an imminent collision threat reported by the bridge. The technical and communicative demands instantly exceed individual working memory capacity. Pedagogical objective: Facilitate expansive learning via distributed team cognition. The engine room team faces a systemic contradiction (a double bind) where adherence to standard protocols conflicts with system survivability. To succeed, the team must collectively forge a new, ad-hoc operational model: restructuring watchkeeping roles, dynamically reallocating physical resources, and managing closed-loop crisis communication to secure the socio-technical system.

5. Discussion and Conclusions

The transition of modern commercial vessels towards highly automated, complex socio-technical systems necessitates a paradigm shift in Marine Engineering SBL. The proposed three-tier socio-technical framework directly challenges the prevailing assessment conventions, such as those implicitly encouraged by the IMO Model Course 2.07. While the mastery of Standard Operating Procedures (SOPs) is non-negotiable for maritime safety, the framework posits that treating mechanical execution as the ultimate pedagogical goal is flawed. If SBL design remains fixated on well-structured problems, institutions risk inducing the expertise reversal effect in advanced learners, thereby stunting the development of dynamic diagnostic reasoning.

By integrating Experiential Learning, Reflective Practice, and Expansive Learning through the regulatory mechanism of Cognitive Load Theory, this framework provides a structured pathway for marine engineering SBL exercise designers. It shifts the educational focus from the device to the activity. The simulator is conceptualized not merely as a high-fidelity technological replica, but as a mediating tool that supports the linear escalation from individual cognitive schema construction (Level 1) to dynamic troubleshooting (Level 2), and ultimately to distributed team cognition under extreme socio-technical pressure (Level 3).

Implementing this framework, however, presents substantial challenges for MET institutions. It requires a shift in the instructor's role. Instructors must transition from being evaluators of technical checklists to active facilitators of cognitive and socio-technical development. They must possess the pedagogical competence to read the cognitive load of the engine room team in real-time, escalating or de-escalating the scenario's complexity to prevent working memory overload or cognitive disengagement. Consequently, future 'Train the Trainer' programmes within the maritime domain must prioritize cognitive psychology and socio-technical systems theory alongside technical proficiency.

Furthermore, the successful application of this framework is fundamentally contingent upon the quality of the broader academic curriculum. Before engaging in high-level SBL, students must possess a robust theoretical foundation and the cognitive capacity to abstract and generalize phenomena, rather than merely recalling isolated technical facts. If student groups consistently fail to resolve Level 3 ill-structured problems, simply de-escalating the scenario back to Level 2 may not yield better learning outcomes. Instead, such repeated failures likely indicate a critical deficit in their theoretical understanding of complex system dynamics. Future research must investigate the theoretical prerequisites required for expansive learning in SBL, ensuring that classroom instruction adequately equips students with the capacity for systemic reflection.

In conclusion, this study answers the research question by defining the essential aspects of a foundational SBL framework for higher education marine engineering. The framework successfully elevates simulator training from a mechanical exercise to a collaborative problem-solving activity.

As a conceptual synthesis, the primary limitation of this study is the absence of empirical validation. Therefore, future research must focus on operationalizing this framework in active MET curricula. Researchers

and exercise designers are encouraged to implement progressive scenarios, such as the Pilotage & Power Management Escalation shown in this study, and collect empirical data on cognitive load, shared situational awareness, and learning outcomes. Furthermore, a critical area for future investigation is the empirical delineation between Level 2 and Level 3 scenarios. Research must establish clear parameters that define the threshold where an ill-structured diagnostic problem (Level 2) escalates beyond individual cognitive capacity into an asymmetrical crisis requiring distributed team cognition (Level 3). Only through rigorous empirical testing and iterative refinement can marine engineering SBL fully align with the complex realities of the modern digital ocean.

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Unmasking the Hidden Waves of Distress: A Latent Profile Analysis of Seafarers' Anxiety and Depression

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Abstract: Seafarers' mental health is a critical issue impacting crew retention and operational safety, yet research often overlooks the diverse ways anxiety and depression co-manifest. Adopting a person-centred approach, this study used Latent Profile Analysis (LPA) on a sample of 991 Chinese seafarers to identify distinct mental health profiles based on their anxiety and depression symptoms. Five distinct profiles were identified: 'Low-Symptom' (5.6%), 'Predominantly Depressive' (24.3%), 'Moderate Distress' (42.1%), 'High Depression-Moderate Anxiety' (22.2%), and 'High Co-occurring Symptoms' (5.8%). Subsequent analysis revealed that profiles characterised by more severe symptoms were associated with lower life satisfaction and higher work-family conflict. Notably, the 'Predominantly Depressive' group reported life satisfaction as low as the 'High Co-occurring Symptoms' group. These findings challenge one-size-fits-all support models and provide an empirical basis for developing targeted, profile-based interventions to improve seafarer well-being and enhance maritime safety.

Keywords: seafarer mental health; Latent Profile Analysis; anxiety and depression; life satisfaction; work-family conflict

1. Introduction

Seafarers are the lifeblood of the global economy, facilitating over 80% of world trade under uniquely demanding conditions. This vital role, however, is set against a backdrop of a professional environment characterised by a confluence of stressors unlike those in most land-based occupations (Aldieri et al., 2026; Li et al., 2022). These challenges range from the physical, such as noise and confinement, to a more insidious set of psychosocial stressors, including prolonged isolation from family, cross-cultural conflicts, and onboard bullying (Jensen, 2021; Yuen et al., 2020). Critically, recent evidence suggests that it is these social and psychological pressures, rather than traditionally cited hardships like contract length, that are the strongest drivers of seafarers' intentions to leave the profession (Svetina et al., 2024). The COVID-19 pandemic further amplified this distress, with extended contracts and unrelenting work pressure pushing many to their limits (Qin et al., 2021; Slišković, 2020).

Unsurprisingly, this high-pressure environment takes a significant toll on mental health, with anxiety and depression emerging as the most prevalent issues (Sánchez-González et al. 2024). Studies have reported alarming rates, with some finding over 40% of seafarers experiencing depressive symptoms during the pandemic (Qin et al., 2021) and others reporting concurrent rates of 30% for anxiety and 37% for depression (Zamora et al., 2021). While these figures establish seafarers as a highly vulnerable group, many studies stop at reporting prevalence rates or treat these conditions as separate issues. The significance of studying their comorbidity—their simultaneous occurrence—extends far beyond individual suffering and strikes at the heart of two of the maritime industry's most pressing challenges: crew retention and operational safety.

The imperative to understand this comorbidity is twofold. First, in an era where the industry faces a record shortage of senior officers (Drewry, 2023), workforce stability is paramount. Svetina and colleagues (2024) provide compelling evidence that negative emotional states, including anxiety and depression, are powerful predictors of a seafarer's intention to quit. Mental health issues are therefore not merely a private welfare concern but a direct driver of a worsening manpower crisis. Second, from another critical angle, the mental state of the crew is inextricably linked to operational safety. Yuen et al. (2020) revealed that burnout, a condition

highly correlated with depression, significantly diminishes safety-conscious behaviours onboard. A seafarer grappling with the cognitive fog of comorbid anxiety and depression experiences depleted attentional resources and impaired decision-making (Mo et al., 2023), posing a direct risk to the vessel, its cargo, and its crew.

Despite its importance, the nuanced patterns of how anxiety and depression co-manifest within the seafarer population remain largely unexplored. Traditional variable-centred research, which examines average relationships between variables, masks the significant heterogeneity within the group (Spurk et al. 2020). It fails to answer crucial questions: Are there distinct subgroups, such as a "high anxiety-low depression" group or a "predominantly depressed" group? To address this gap, our study adopts a person-centred approach using Latent Profile Analysis (LPA). This method allows us to move beyond group averages to identify distinct subgroups of seafarers based on their shared patterns of anxiety and depression symptoms. Our objectives are to: (1) identify the latent profiles of anxiety and depression among Chinese seafarers; (2) examine how these profiles differ in terms of life satisfaction and work-family conflict; and (3) provide an empirical basis for developing differentiated, precise interventions that can more effectively support seafarer well-being, improve retention, and enhance maritime safety.

2. Methods

2.1. Participants and Procedure

This study was reviewed and approved by the Institutional Review Board (IRB) of Dalian Maritime University. All procedures were conducted in accordance with the ethical standards of the institution. This study targeted active Chinese seafarers. To reach this specific population, we collaborated with several Chinese shipping companies who facilitated access to their crews. Data were collected via an online questionnaire distributed by ship captains to their crew members. Although the survey link was distributed by ship captains to facilitate access to the crew, captains were not informed of who completed the questionnaire nor had access to any individual responses. All data were collected directly through an anonymous online platform managed by the research team. Participants were explicitly informed that participation was entirely voluntary, that their responses would remain confidential, and that neither their employers nor their captains would be able to identify them or view their answers. A final valid sample of 991 seafarers was obtained for analysis. The sample was overwhelmingly male (99.4%, n = 985), with 6 female participants (0.6%). The average age of participants was 37.89 years (SD = 8.71), and their average sea service was 12.86 years (SD = 7.93). Regarding marital status, the majority were married (75.0% in total; 70.4% with children and 4.6% without), while 23.3% were unmarried. A small percentage were divorced (1.4%) or widowed (0.2%).

2.2. Measures

Anxiety and Depression. The core indicators for our analysis were anxiety and depression. To measure these constructs, we used revised and simplified Chinese versions of the Depression and Anxiety sub-scales from the Symptom Checklist-90 (SCL-90; Derogatis, 1975). The SCL-90 is a classic and widely recognised instrument for psychological symptom screening, and its sub-scales have been extensively validated in Chinese populations. In the current sample, both sub-scales demonstrated good to excellent internal consistency (Cronbach's α = .81 for Depression; α = .89 for Anxiety), providing a solid basis for their use as indicator variables in the Latent Profile Analysis.

Life Satisfaction. To assess the consequences of mental health profiles, we measured subjective well-being using the 5-item Satisfaction with Life Scale (SWLS; Diener et al., 1985). This scale asks participants to provide a global cognitive judgement of their life quality. The scale showed good reliability in our sample (Cronbach's α = .87).

Work-Family Conflict. As another key outcome, work-family conflict was measured using the 10-item scale developed by Netemeyer et al. (1996). This scale captures the bidirectional nature of this stressor. Its reliability in this study was also high (Cronbach's α = .88).

2.3. Data Analysis Strategy

Our data analysis proceeded in three main steps. First, we conducted descriptive statistics and correlation analyses in SPSS 26.0 to get an initial overview of the tested variables.

Second, the central part of our analysis involved using Latent Profile Analysis (LPA) with Mplus 8.3 to identify distinct subgroups of seafarers based on their scores on the anxiety and depression. To find the best-fitting model, we compared solutions with two to seven profiles. The final decision was based on a combination of statistical fit indices (lower AIC, BIC, and aBIC values), classification accuracy (Entropy > .80), and likelihood ratio tests (LMR-LRT and BLRT). Crucially, the theoretical coherence and practical interpretability of the profiles were also key considerations in selecting the final model.

Third, once the optimal profile solution was identified, we used the BCH (Bolck-Croon-Hagenaars) method together with Bonferroni correction in Mplus to examine the differences in outcomes across the profiles. This modern approach treats profile membership as the independent variable and life satisfaction and work-family conflict as dependent variables, while correcting for any classification uncertainty to provide more accurate and unbiased results.

3. Results

3.1. Preliminary Analysis

Table 1 displays the descriptive statistics and Pearson correlations for all study variables. As expected, anxiety and depression were strongly and positively correlated ($r = .55$, $p < .001$). Both distress indicators were also moderately associated with higher work-family conflict. Conversely, life satisfaction showed significant negative correlations with depression, anxiety, and work-family conflict, with the strongest inverse relationship observed with work-family conflict ($r = -.62$, $p < .001$). These preliminary findings confirm the expected relationships among the key variables.

Table 1. Results of the Descriptive Statistics and Pearson Correlations among Variables.

	Mean	SD	1	2	3	4	5
1. Depression	3.43	0.76					
2. Anxiety	2.12	0.83	0.55***				
3. Life Satisfaction	3.21	0.79	-0.53***	-0.42***			
4. Work-Family Conflict	3.62	0.95	0.45***	0.42***	-0.62***		
5. Age	37.89	8.71	0.05	-0.02	0.02	0.06	
6. Work Year	12.86	7.93	0.14***	0.07*	-0.04	-0.04	0.81*

Note. *** $p < .001$, ** $p < .01$, * $p < .05$.

3.2. Latent Profiles of Seafarer Anxiety and Depression

After comparing the fit indices for models with two to seven classes, the five-profile solution was selected as the optimal model (see Table 2 and Figure 1). Although AIC, BIC, and aBIC values continued to decrease for the six- and seven-profile solutions, several considerations supported the five-profile model as the most appropriate choice. First, the marginal improvement in fit indices from five to six and seven profiles was relatively small compared with the substantial reductions observed between earlier solutions, suggesting diminishing returns. Second, the six- and seven-profile solutions produced very small classes (as low as 4%), which raised concerns about statistical stability and substantive interpretability. Third, the Entropy value for the five-profile solution (.929) was higher than that of the six-profile solution (.904), indicating better classification accuracy. Finally, the five-profile model offered the clearest theoretical coherence, with each profile representing a distinct and substantively meaningful pattern of symptoms. Taken together, the five-profile solution provided the best balance of parsimony, classification quality, and interpretability.

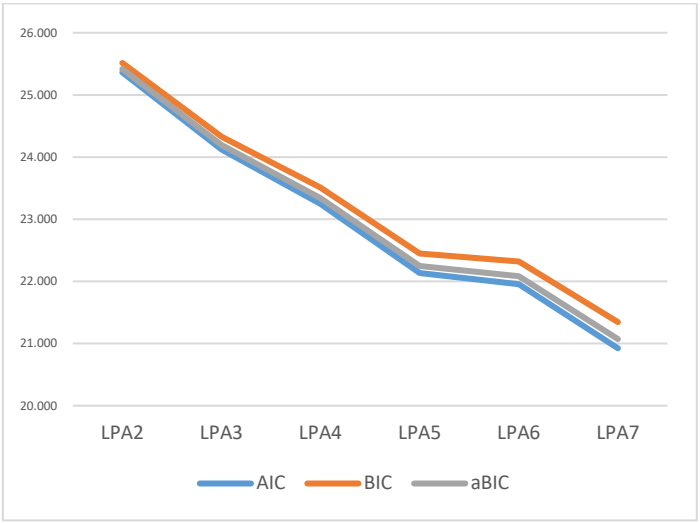


Figure 1. Elbow Plot of Model Fit Indices.

Table 2. Fit Indexes of the Latent Profile Model of Seafarers' Anxiety and Depression.

	AIC	BIC	aBIC	Enotrpy	classification	LMR	BLRT
LPA2	25362	25514	25416	0.868	0.63/0.37	<.001	<.001
LPA3	24121	24327	24194	0.918	0.61/0.32/0.06	<.001	<.001
LPA4	23249	23509	23340	0.927	0.51/0.26/0.17/0.06	<.001	<.001
LPA5	**22136**	**22449**	**22246**	**0.929**	**0.42/0.24/0.22/0.06/0.06**	**<.001**	**<.001**
LPA6	21954	22321	22083	0.904	0.36/0.22/0.15/0.13/0.08/0.06	<.001	<.001
LPA7	20923	21345	21071	0.906	0.35/0.26/0.14/0.10/0.06/0.04/0.04	<.007	<.001

The five latent profiles, representing distinct patterns of mental health distress, were named as follows (see Figure 2 in detail):

Profile 1: "Low-Symptom" (5.6%). This small group was characterised by very low scores on both anxiety and depression, representing an ideal state of mental well-being.

Profile 2: "Predominantly Depressive" (24.3%). This group showed elevated scores on depression but relatively low scores on anxiety.

Profile 3: "Moderate Distress" (42.1%). This was the largest group, with seafarers reporting moderate levels of both anxiety and depression symptoms.

Profile 4: "High Depression-Moderate Anxiety" (22.2%). This profile was defined by high levels of depression combined with moderate levels of anxiety.

Profile 5: "High Co-occurring Symptoms" (5.8%). This high-risk group exhibited the most severe symptoms of both anxiety and depression, indicating a heightened level of self-reported psychological distress that may warrant priority attention.

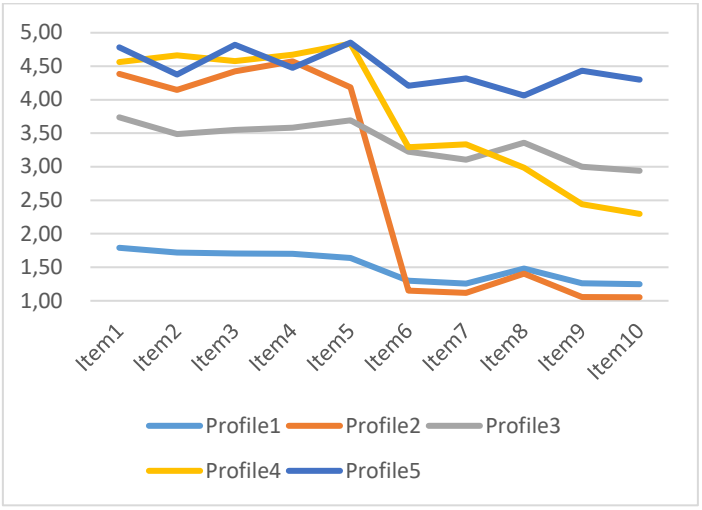


Figure 2. The Five Latent Profiles of Anxiety-Depression

Note. The Latent Profile Analysis was conducted using individual items from the Depression and Anxiety sub-scales. Items 1–5 represent depression items, and Items 6–10 represent anxiety items

3.3. Mental Health Consequences of Different Latent Profiles

The BCH analysis revealed significant differences across the five profiles in both life satisfaction and work-family conflict (all $p < .001$, as indicated by post-hoc comparisons in Table 3). The results showed a clear pattern where increased psychological distress was associated with poorer outcomes. Specifically, work-family conflict increased progressively across the profiles, from the "Low-Symptom" group to the "High Co-occurring Symptoms" group. While a similar general downward trend was observed for life satisfaction, the pattern was not strictly linear.

As expected, the "Low-Symptom" group (Profile 1) reported the highest life satisfaction ($M = 4.29$), and the "High Co-occurring Symptoms" group (Profile 5) consistently showed the worst outcomes, with the lowest life satisfaction ($M = 2.69$) and the highest work-family conflict ($M = 4.57$). The analysis also uncovered two particularly insightful findings. First, despite having lower anxiety, the "Predominantly Depressive" group (Profile 2) reported a level of life satisfaction ($M = 2.75$) that was not statistically different from the "High Co-occurring Symptoms" group ($M = 2.69$; $d = 0.08$), suggesting that severe depressive symptoms alone can be as detrimental to life quality as comorbid conditions. Second, in a contrasting result, the work-family conflict experienced by the "Predominantly Depressive" group ($M = 3.07$) was not significantly different from that of the "Low-Symptom" group ($M = 2.92$; $d = -0.05$). This indicates a more complex relationship, where the spillover of distress into the family domain might be more strongly associated with anxiety or the combination of symptoms, rather than by depression alone.

Table 3. Comparison of Life Outcome Indicators Across Latent Profile Groups.

	Life Satisfaction						Work-Family Conflict					
	M_1	(SD1)	M_2	(SD2)	M_{diff}	*d*	M_1	(SD1)	M_2	(SD2)	M_{diff}	*d*
Profile 1 r vs Profile 2	4.29	0.92	2.75	0.78	1.53	1.90*	2.92	2.82	3.07	3.05	-0.15	-0.05
Profile 1 r vs Profile 3	4.29	0.92	3.18	0.63	1.11	1.64*	2.92	2.82	3.60	3.02	-0.68	-0.23*
Profile 1 r vs Profile 4	4.29	0.92	3.57	0.71	0.71	0.94*	2.92	2.82	4.10	3.47	-1.18	-0.35*
Profile 1 r vs Profile 5	4.29	0.92	2.69	0.92	1.59	1.73*	2.92	2.82	4.57	3.86	-1.65	-0.49*
Profile 2 r vs Profile 3	2.75	0.78	3.18	0.63	-0.43	-0.62*	3.07	3.05	3.60	3.02	-0.53	-0.18*
Profile 2 r vs Profile 4	2.75	0.78	3.57	0.71	-0.82	-1.10*	3.07	3.05	4.10	3.47	-1.03	-0.32*
Profile 2 r vs Profile 5	2.75	0.78	2.69	0.92	0.06	0.08	3.07	3.05	4.57	3.86	-1.50	-0.47*
Profile 3 r vs Profile 4	3.18	0.63	3.57	0.71	-0.39	-0.60*	3.60	3.02	4.10	3.47	-0.50	-0.16*
Profile 3 r vs Profile 5	3.18	0.63	2.69	0.92	0.49	0.73*	3.60	3.02	4.57	3.86	-0.97	-0.31*

Profile 4 r vs Profile 5	3.57	0.71	2.69	0.92	0.88	1.16*	4.10	3.47	4.57	3.86	-0.47	-0.13*

Note. Profile 1 = Low-Symptom, Profile 2 = Predominantly Depressive, Profile 3 = Moderate Distress, Profile 4 = High Depression-Moderate Anxiety, Profile 5 = High Co-occurring Symptoms. r refers to the reference group.

4. Discussion and Conclusion

This study sought to move beyond a generalised view of seafarer distress by employing a person-centred approach, and our findings confirm the value of this perspective. The Latent Profile Analysis successfully identified five distinct and meaningful mental health profiles among seafarers: Low-Symptom, Predominantly Depressive, Moderate Distress, High Depression-Moderate Anxiety, and High Co-occurring Symptoms. This core finding powerfully demonstrates that the mental health landscape of seafarers is not a monolith but is instead characterised by significant heterogeneity. The subsequent analysis, which revealed a clear gradient effect where life satisfaction decreased and work-family conflict increased with profile severity, validates the real-world relevance of these groupings and challenges the efficacy of any one-size-fits-all approach to maritime mental well-being.

The interpretation of these profiles, particularly the nuanced differences between them, offers critical insights. The High Co-occurring Symptoms group (5.8%), though small, represents the epicentre of risk. Experiencing the lowest life satisfaction and highest work-family conflict, they may represent a group of particular concern for the industry: a potentially elevated risk of voluntary turnover associated with negative emotional states (Svetina et al., 2024) and a possible safety-related concern, given prior evidence linking psychological distress with diminished cognitive functioning and reduced safety-conscious behaviour (Mo et al., 2023; Yuen et al., 2020). It should be noted, however, that the present study did not directly measure safety incidents or performance outcomes.

Perhaps most revealing is the Predominantly Depressive group (24.3%). Their profile—high depression with low anxiety—and their notably low life satisfaction, which was statistically indistinguishable from the High Co-occurring Symptoms group, may be tentatively interpreted as resembling a pattern consistent with occupational burnout, although burnout was not directly measured in this study. This interpretation should therefore be regarded as a hypothesis for future research rather than a confirmed conclusion. This possible link aligns with findings that link unrelenting work pressure and fatigue directly to depression (Qin et al., 2021). Their low anxiety could potentially reflect a state of emotional exhaustion and resignation that may follow a prolonged period of stress. This suggests that the presence of severe depression alone is sufficient to devastate a seafarer's quality of life to its lowest point. Equally intriguing is the finding that this group's level of work-family conflict was not significantly different from the Low-Symptom group. This may indicate that their distress is more internalised—characterised by anhedonia and hopelessness—than driven by the external pressures of role conflict, or perhaps that work-family conflict is a pervasive, baseline stressor for all seafarers regardless of their specific mental health profile.

The two largest profiles, Moderate Distress (42.1%) and High Depression-Moderate Anxiety (22.2%), collectively represent nearly two-thirds of the sample. These seafarers are not in acute crisis but are clearly struggling. They constitute the most critical population for preventative and early intervention efforts. These are the individuals who may be most susceptible to the pressures of long voyages, social media-induced stress (Zamora et al., 2021), or bullying (Svetina et al., 2024), and who, without support, are at high risk of transitioning into the more severe profiles over time.

The practical implications of these findings are substantial. They call for a shift away from uniform support programmes towards a profile-based, tiered system of care. For the High Co-occurring Symptoms group, the focus should be on crisis intervention and immediate, high-intensity support, such as 24/7 confidential counselling and clear protocols for medical sign-off. For the Predominantly Depressive group, interventions targeting burnout-related symptoms, such as organisational changes to enforce rest and improve working conditions (Qin et al., 2021), might prove more effective than standard anxiety-management techniques. The vast majority of seafarers in the intermediate profiles may benefit most from preventative strategies and skill-building initiatives: providing accessible online training for stress management, fostering supportive leadership, and building psychological capital to enhance resilience and safety behaviour (Yuen et al., 2020). Finally, the Low-Symptom group (5.6%) represents a vital organisational asset; they can be identified and empowered to act as peer-support leaders, helping to cultivate a positive mental health culture onboard.

It is important to acknowledge the limitations of our study, which also highlight avenues for future research. Firstly, the cross-sectional design means we cannot infer causality or developmental trajectories, and any references to seafarers "moving between" profiles should be regarded as conceptual rather than empirically demonstrated. Longitudinal research is a crucial next step. Secondly, our sample was composed of Chinese seafarers, and cultural factors may shape how emotional symptoms are experienced, expressed, and reported. In particular, cultural norms around emotional restraint and stigma toward mental health issues in Chinese contexts may influence the structure and prevalence of the identified profiles. Replicating this analysis across different nationalities is therefore necessary to establish cross-cultural generalisability. Thirdly, the sample was almost entirely male (99.4%), which, although broadly representative of the seafaring workforce, limits the generalisability of the findings to female seafarers. Future research should aim to include a more gender-balanced sample to explore whether the identified profile structure holds for women seafarers. Fourthly, although the survey was anonymous and captains had no access to individual responses, the fact that questionnaires were distributed through ship captains may have introduced perceived hierarchical pressure or social desirability bias, potentially affecting response patterns and possibly leading to underreporting of distress. Future studies could consider alternative recruitment strategies that bypass the ship hierarchy entirely. Lastly, future models could be enriched by including direct measures of burnout, sleep quality, and specific onboard social stressors to empirically test the interpretations offered here. Incorporating objective data, such as physiological metrics (Mo et al., 2023), could also provide a more holistic understanding.

In conclusion, this study unmasks the diverse waves of distress among seafarers, replacing a blurry, generalised picture with a high-resolution map of distinct psychological profiles. By revealing who is struggling and how, our research provides the maritime industry with a crucial tool. It paves the way for the development of more efficient, compassionate, and targeted interventions that can better protect the well-being of its most valuable asset—its people—while simultaneously safeguarding the stability and safety of global maritime operations.

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Human-centred Safety Practices in the Handling of Dangerous Goods in Maritime-Port Systems

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Abstract: The transport and handling of dangerous goods represent a significant challenge for maritime safety and environmental protection within increasingly complex maritime-port systems. Despite comprehensive international regulations, operational incidents continue to occur, often associated with human and organisational factors rather than technical failures alone. This study investigates the role of human factors, safety culture and professional training in dangerous goods handling within maritime-port environments. A mixed-methods approach was adopted, combining documentary analysis, questionnaire survey of 56 maritime professionals, and field observations of dangerous goods container operations and bunkering activities in Portuguese maritime-port contexts. The findings reveal important gaps between regulatory requirements and operational practice, including limited consultation of IMDG procedures, inconsistent incorporation of dangerous goods scenarios into safety drills, insufficient company-promoted training and normalised procedural deviations observed during bunkering and container handling operations. Respondents also demonstrated strong interest in continuous professional development and additional dangerous goods training. The study highlights the importance of organisational safety culture, operational awareness and Maritime Education and Training (MET) in strengthening hazardous cargo safety management within modern maritime-port systems.

Keywords: dangerous goods; maritime safety; human factors; safety culture; maritime training

1. Introduction

The transport and handling of dangerous goods, also referred to as hazardous materials (HAZMAT), play a fundamental role in global trade and maritime logistics. Large volumes of such cargoes are transported daily through maritime and port systems, supporting industrial production, energy supply chains and international commerce. Estimates suggest that dangerous goods account for a substantial share of global container traffic — with some analyses placing the figure at approximately 40% (Maternová and Materna, 2022) — making their safe management an operational imperative of the highest order. However, accidents involving dangerous goods continue to represent significant risks to human life, port infrastructure and the marine environment, with incidents such as cargo fires, explosions and misdeclared dangerous goods demonstrating the complexity and vulnerability of maritime-port operations involving hazardous cargoes.

International regulatory frameworks such as the International Maritime Dangerous Goods (IMDG) Code, the SOLAS Convention (1974) and the MARPOL Convention (73/78) establish detailed procedures for classification, packaging, segregation, stowage and handling of dangerous goods (IMO, 2024). Despite these comprehensive regulations, operational incidents and safety deviations continue to occur across maritime supply chains. Recent studies indicate that many of these events are associated not only with technical failures, but also with human and organisational factors, including inadequate training, communication failures, procedural non-compliance and weak safety culture (Khan et al., 2022). Up to 25% of serious fires aboard container vessels have been attributed to misdeclared dangerous goods (Maternová and Materna, 2022), underscoring the human dimension in risk causation.

According to Reason (1997), accidents in complex operational systems rarely result from a single technical failure, but rather from the interaction between organisational weaknesses, unsafe practices and human error. In maritime-port environments, safety performance is therefore strongly influenced by operational behaviour,

decision-making processes, safety awareness and organisational commitment to continuous professional development. The problem is not merely technical: compliance with international regulations, while necessary, is insufficient when the professionals responsible for implementation lack the competence, training and organisational support to apply those regulations consistently in operational contexts.

At the same time, the maritime sector is undergoing progressive digitalisation, with increasing implementation of cargo monitoring systems, electronic documentation and decision-support tools. Nevertheless, the effectiveness of such technologies depends largely on the competence and preparedness of maritime professionals to integrate digital tools into daily operational practice. Consequently, maritime education, continuous training and safety culture remain central elements in the development of safe and sustainable maritime operations.

This paper investigates the role of human factors, safety culture and training practices in the handling of dangerous goods within maritime-port environments, based on evidence collected from Portuguese maritime professionals and operational settings. Drawing on a mixed-methods design combining documentary analysis, questionnaire survey and field observations conducted in selected Portuguese ports and on board merchant vessels, the paper aims to generate empirically grounded insights and recommendations in support of more effective, human-centred safety strategies for the maritime-port sector.

2. Literature Review

2.1. Human Factors and Safety Culture in Maritime Operations

Human factors have long been recognised as a critical component of maritime safety. Despite technological developments and increasingly sophisticated regulatory frameworks, accidents in maritime operations continue to be strongly associated with human and organisational factors rather than with technical failures alone. Reason (1997) established that accidents in complex systems frequently result from the interaction between unsafe acts, organisational weaknesses and latent conditions embedded within operational environments. Safety performance therefore depends not only on procedures and regulations, but also on behavioural practices, communication, decision-making processes and organisational culture.

Khan et al. (2022) argue that operational incidents are often linked to inadequate training, weak safety culture, communication failures and insufficient organisational support. Hetherington et al. (2006) highlight that human error in maritime transport is frequently influenced by fatigue, workload, lack of situational awareness and ineffective safety management practices. These findings demonstrate that safety culture plays a fundamental role in shaping operational behaviour and compliance with safety procedures. Even professionals with adequate theoretical knowledge frequently fail to apply safety procedures consistently — a knowledge-action gap shaped by organisational norms and the perceived legitimacy of safety rules (Rothblum, 2000).

In maritime-port environments, dangerous goods handling operations involve complex interactions between ship crews, terminal operators, logistics personnel and regulatory authorities. Such operational complexity increases the relevance of human competence, procedural awareness and continuous professional training as essential elements of effective risk management.

2.2. Dangerous Goods Handling and IMDG Code Compliance

The IMDG Code provides the principal international framework for the safe transport of dangerous goods by sea, establishing detailed requirements for classification, packaging, labelling, documentation, stowage and segregation of hazardous substances. Adopted as a recommendation in 1965 and made mandatory under SOLAS from 2004, the Code is updated on a biennial cycle to incorporate new substances and evolving best practices (IMO, 2024). In Portugal, these obligations are transposed through Decree-Law 180/2004, implementing Directive 2002/59/EC, which establishes mandatory pre-arrival notification of dangerous goods to port authorities.

Maternová and Materna (2022) identify misdeclared dangerous goods as a persistent safety problem in containerised transport, with intentional misdeclaration accounting for approximately 33% of all incorrectly declared shipment incidents. Hervás-Peralta et al. (2020) further demonstrate that the absence of dedicated dangerous goods storage zones in port terminals creates structural vulnerabilities that regulatory compliance alone cannot mitigate, while Tseng and Pilcher (2023) identify detection capability as the critical moderating

variable in port dangerous goods risk management. These findings collectively indicate that regulatory compliance cannot substitute for sound operational practice and informed human judgement.

2.3. Maritime Training and Professional Development

Continuous professional training represents a key element in the development of safe maritime operations. The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) establishes minimum requirements for maritime education, competence and professional certification within the shipping industry (IMO, 2017). However, research consistently demonstrates that initial certification is insufficient to sustain safe practice in a dynamic regulatory environment where the IMDG Code is revised biennially and new hazardous substances enter commercial circulation continuously.

The relationship between training and safety compliance is well documented in the scientific literature. Burke et al. (2006) conducted a meta-analysis of safety training effectiveness across industries and found that programmes emphasising hands-on practice, scenario simulation and behavioural rehearsal produced significantly stronger transfer effects than knowledge-only approaches — a finding directly relevant to maritime dangerous goods training contexts. Hutchinson et al. (2022), in a meta-analysis of 100 samples from 90 studies, demonstrated that safety training interventions improve compliance and participation across industries, with high-risk sectors showing particularly strong gains — reinforcing the case for sustained training investment in maritime dangerous goods contexts.

Veiga (2002) and Bartusevičienė (2020) emphasise that Maritime Education and Training (MET) is central to developing safety culture in shipping, particularly in contexts of increasing technological complexity. O'Connor et al. (2011) demonstrate that safety climate measurement is most effective in organisations where leadership visibly prioritises safety, while Zohar (2002) shows that supervisors who systematically reinforce safety behaviour create substantially safer working environments — suggesting that training deficits are ultimately an organisational leadership problem as much as a resource allocation problem.

2.4. Digitalisation and Human-centred Safety Support

Digital technologies are increasingly being integrated into maritime logistics and dangerous goods management systems. Durlik et al. (2023) demonstrate that IoT sensors, machine learning and real-time analytics significantly enhance port safety, navigation monitoring and environmental compliance — capabilities with direct relevance to dangerous goods tracking. More recent applications have extended these tools to emergency communication and decision-support systems for dangerous goods risk assessment (Chovanec et al., 2026; Kollár et al., 2026). Kim et al. (2021) further highlight the growing relevance of simulator-based education in the development of maritime professional competencies.

However, technological solutions alone do not eliminate operational risks. The effectiveness of digital systems remains dependent on human competence, organisational preparedness and the capacity of maritime professionals to integrate technological tools into operational practice. The central challenge is therefore not to replace human agency but to enhance it: to develop digital ecosystems in which well-trained professionals are supported by reliable information and effective decision-support tools. This human-centred perspective on digitalisation underpins the analytical framework of this study and aligns with the theme of IAMUC 2026.

3. Methodology

3.1. Research Approach

This study adopted an interpretive research paradigm based on a mixed-methods approach combining qualitative and quantitative research techniques (Creswell, 2014). As Johnson and Onwuegbuzie (2004) argue, mixed-methods designs suit contexts where triangulation across data sources strengthens validity by combining statistical and contextual evidence. The questionnaire instrument was developed around five thematic dimensions — safety awareness, IMDG consultation, in-voyage monitoring, training and organisational support, and safety culture — and pre-tested prior to full administration. The integration of all three data collection methods enabled a broader understanding of the relationship between regulatory requirements, operational behaviour and safety culture.

3.2. Data Collection

Data collection was conducted through three complementary methods: documentary analysis, questionnaire survey and field observations.

The documentary analysis covered the IMDG Code, the SOLAS and MARPOL Conventions, MSC.1/Circ.1216 (2007), and the principal Portuguese legal instruments: Decree-Law 180/2004 (transposing Directive 2002/59/EC, establishing the mandatory notification regime for dangerous goods at national ports) and Decree-Law 41-A/2010, as amended by Decree-Law 99/2021 (regulating land transport of dangerous goods and the conselheiro de segurança role under ADR/RID — the model for the study's fifth recommendation).

A structured anonymous questionnaire was administered to 56 deck officers and masters holding current STCW certification and actively serving or recently active aboard merchant vessels. It collected information on operational routines, IMDG consultation, monitoring practices and perceptions of training and organisational safety support. Full details are available in Pessoa (2025).

Field observations were conducted at three Portuguese port terminals: TCSA – Sotagus (Port of Lisbon), TCL (Port of Leixões) and Nogarport (Port of Viana do Castelo). To preserve analytical neutrality and operational confidentiality, these terminals are referred to throughout this study as Port A, Port B and Port C, in a random order that does not necessarily correspond to the sequence in which they are listed above. A total of three VLSFO bunkering operations (aboard Vessels A, B and C), observed as hazardous fuel-handling operational contexts under MARPOL and SOLAS frameworks, and sixteen dangerous goods container movements regulated under the IMDG Code were observed over approximately three months in 2024 (Pessoa, 2025).

3.3. Data Analysis

Quantitative questionnaire data were analysed using descriptive statistics including frequency distributions and cross-tabulations. Qualitative data from field notes, observations and open-ended responses were analysed using content analysis following the three-phase protocol described by Bardin (2011): pre-analysis, systematic coding and interpretive inference. Five thematic categories were identified: (1) safety awareness and knowledge of norms; (2) compliance with procedures; (3) monitoring and inspection practices; (4) training and organisational support; and (5) safety culture (Pessoa, 2025). Results are presented and discussed thematically in the following section.

4. Results and Discussion

4.1. Operational Exposure and Safety Awareness

73.2% of respondents worked on vessels regularly transporting dangerous goods (Pessoa, 2025). Regarding safety awareness, 80% indicated familiarity with the IMDG Code, yet only 45% applied it regularly; 89.3% rated their knowledge between 2 and 4 on a 1–5 scale, with 42.9% selecting the mid-point.

Table 1. Key quantitative findings by thematic category (source: Pessoa, 2025).

Thematic Category	Key Indicator (n=56)	Main Finding
Safety awareness	80% familiar with IMDG; only 45% apply it regularly	Persistent knowledge-action gap
DG drills	66% never/rarely include DG in drills; only 3.6% almost always	Systematic failure to reinforce operational knowledge
IMDG consultation & monitoring	>30% never/rarely consult IMDG during voyages; only 19.6% monitor DG cargo twice daily	IMDG compliance treated as pre-departure obligation
Procedural compliance	42.9% acknowledge procedures often not fully followed; <30% consistent compliance	Gap between regulation and operational practice

Company training provision	66.1% never received employer DG training; 89.3% would welcome it	Structural organisational investment deficit
Professional development	57.1% support mandatory STCW DG renewal; 67.8% want further training	Professional appetite exceeds organisational provision

This knowledge-action gap is consistent with Reason's (1997) account of latent conditions that inhibit the translation of competence into reliable operational behaviour; when safety compliance is perceived as bureaucratic, it is selectively applied, particularly under commercial pressure (Rothblum, 2000). Critically, 66% of respondents never or very rarely incorporate dangerous goods scenarios into safety drills — only 3.6% do so almost always — a systematic failure to reinforce procedural knowledge through the hands-on practice identified by Burke et al. (2006) as most effective.

4.2. IMDG Documentation Consultation and In-Voyage Monitoring

Routine consultation of IMDG documentation during voyages was notably infrequent. More than 30% of respondents indicated that they 'never' or only 'very rarely' consulted the IMDG Code or Dangerous Goods Declarations (DGDs) during voyages on which dangerous cargo was aboard. Only 16–22% reported doing so on a regular and preventive basis. In-voyage monitoring of dangerous cargo was similarly inconsistent: 46.7% of respondents reported not monitoring such cargo during navigation, or doing so only selectively depending on the UN class. Only 19.6% confirmed that dedicated monitoring by deck officers occurred at least twice daily (Pessoa, 2025).

These patterns suggest that IMDG compliance is often treated as a pre-departure obligation rather than an integrated element of voyage management, in tension with the continuous monitoring obligations of Decree-Law 180/2004 and Directive 2002/59/EC. Although bunkering operations fall outside the IMDG Code, they were observed as a complementary safety culture context. Three VLSFO bunkering operations at Port C revealed contrasting compliance levels: Vessel A correctly inserted scupper plugs and maintained an unobstructed SOPEP kit; Vessel B failed to insert scupper plugs (a MARPOL non-conformity) and its watchman was absent from the bunkering station on two occasions; on Vessel C the SOPEP kit was obstructed by hoses and tools. In none of the three operations had firefighting equipment been pre-positioned, contrary to SOLAS. This variability illustrates what Reason (1997) describes as violation-tolerant environments, where latent risks only become apparent when a triggering event converts them into catastrophic outcomes.

4.3. Compliance with Procedures: Between Regulation and Practice

The questionnaire data document a significant gap between regulatory prescription and operational reality. Among respondents who carry dangerous cargo, 42.9% acknowledged that specific safety procedures for loading and unloading operations 'often are not fully observed'. A further 28.6% reported following such procedures only when explicitly directed by agents or company management, while fewer than 30% confirmed that procedures are consistently followed in full.

Field observations at Port A and Port B documented satisfactory documentary verification but exhibited the structural limitation identified by Hervás-Peralta et al. (2020): chemical compatibility between co-located containers was not systematically verified. At Port A, containers #7 and #8 bore co-labels for Class 3, Class 2.1 and Class 8 with a Limited Quantity designation — anomalous under IMDG, since a Class 2.1 substance in limited quantities does not require its own hazard label — and this passed gate-entry uncorrected. Port A records document three incidents between 2020 and 2024, including a fire in a container not declared as dangerous goods. At Port B, Class 8 containers were co-located with Class 3 and Class 9 units without sub-class compatibility checks. These findings confirm the concern of Tseng and Pilcher (2023): detection systems relying on visual inspection cannot reliably identify all dangerous goods risks, consistent with Maternová and Materna (2022) on how commercial pressures disadvantage full regulatory compliance.

4.4. Training Deficits and the Organisational Investment Gap

The training dimension reveals the most structurally significant finding of this study. Among all respondents, 66.1% reported having never received any specific training or awareness-raising activity from their employer regarding the safe transport of dangerous goods. A further 17.9% had received such training only in some of the companies where they had worked, with 16.1% reporting consistent provision across all employers (Pessoa, 2025). These figures represent a marked deficit in company-level investment in dangerous goods professional development that is difficult to reconcile with the risk profile of the operations involved.

This finding is consistent with the broader evidence base on safety training effectiveness. Hutchinson et al. (2022), in a meta-analysis encompassing 100 independent samples across a wide range of industries, demonstrated that safety training interventions systematically improve safety compliance and participation, with the effect on safety climate and motivation being particularly pronounced in high-risk industries — precisely the operational environment in which maritime dangerous goods professionals work. The implication is direct: the training deficit documented in this study is not merely a gap in individual knowledge but a structural failure of organisational investment that suppresses safety climate at the very point where its positive effects would be greatest.

Paradoxically, professional appetite for further training is high: 67.8% of respondents expressed a desire to deepen their knowledge, and 89.3% would welcome employer-provided training; 57.1% supported mandatory periodic renewal of STCW dangerous goods certification (Pessoa, 2025). O'Connor et al. (2011) show that safety climate tools produce the most durable behavioural outcomes in organisations where leadership actively reinforces safety. Zohar's (2002) leadership-based intervention model further confirms that supervisors who systematically reinforce safety behaviour achieve significant improvements in subunit performance: regulatory requirements are necessary but insufficient without genuine organisational commitment.

4.5. Safety Culture and Digital Safety Support

Across all dimensions, the data point to a predominantly reactive safety culture. The absence of dangerous goods drills, normalised bunkering deviations, labelling inconsistencies and underinvestment in training reflect an organisational logic in which safety is a compliance obligation rather than a proactive value — consistent with Reason's (1997) characterisation of complacent safety environments. Khan et al. (2022) note that reactive safety management is particularly dangerous in hazardous cargo operations, where latent failures have disproportionately severe consequences.

Positive examples do exist. At Port A, a dedicated first-intervention team with specific dangerous goods training demonstrated that proactive investment in emergency preparedness is both feasible and operationally effective. An expert from the Comissão Nacional do Transporte de Mercadorias Perigosas (CNTMP) reinforced this systemic diagnosis, identifying the absence of a standardised maritime safety advisory role as a structural gap in the Portuguese maritime sector. In the terrestrial modes, Decree-Law 41-A/2010 — as amended by Decree-Law 99/2021 — mandates the designation of a certified safety adviser (conselheiro de segurança) in all companies handling dangerous goods by road or rail. No equivalent obligation exists for the maritime mode, creating a regulatory asymmetry that this study's fifth recommendation seeks to address.

The growing role of digital tools in supporting a more preventive safety culture deserves specific attention. The integration of IoT-based container monitoring, thermal scanning and AI-assisted compatibility checking in port stowage planning could substantially strengthen detection capability beyond what visual inspection alone can achieve (Chovanec et al., 2026; Kollár et al., 2026). Kim et al. (2021) similarly highlights the value of simulator-based training in developing operational preparedness for complex dangerous goods scenarios. However, as the field evidence from this study demonstrates, the availability of documentation systems does not in itself prevent operational deviations: technology and training are complements, not substitutes.

5. Conclusions

This study investigated the role of human factors, safety culture and professional training in dangerous goods handling within Portuguese maritime-port environments, integrating questionnaire evidence from 56 merchant marine officers with field observations of dangerous goods container operations and bunkering activities at three Portuguese port terminals. The convergent finding is unambiguous: technical regulation alone does not guarantee safe dangerous goods handling. Operational safety depends on the interaction between

human competence, organisational culture, continuous training and the effective implementation of safety procedures in daily operations.

The study documented a persistent knowledge-action gap, with awareness of the IMDG Code not translating into consistent operational application. IMDG documentation is infrequently consulted during voyages, in-voyage cargo monitoring is irregular, and normalised procedural deviations were observed across both container handling operations (IMDG) and bunkering activities (MARPOL/SOLAS). Most significantly, 66.1% of surveyed professionals have never received company-provided dangerous goods training — a structural deficit inconsistent with the risk profile of maritime dangerous goods operations and difficult to reconcile with the continuous revision of the regulatory framework those professionals are expected to apply.

The study supports five strategic recommendations: (1) mandatory periodic renewal of STCW dangerous goods certification; (2) systematic scenario-based dangerous goods training integrated into shipboard safety programmes; (3) more robust chemical compatibility verification protocols in port terminals; (4) deployment of digital monitoring tools as enablers of human judgement; and (5) the introduction in Portugal of a dedicated maritime dangerous goods safety advisory role — analogous to the conselheiro de segurança established in the terrestrial modes by Decree-Law 41-A/2010, as amended by Decree-Law 99/2021 — to provide institutional support for compliance guidance and incident reporting.

Future research should extend the sample to include port workers, freight forwarders and company safety officers, and examine the longitudinal effects of training interventions. Cross-national comparative studies within the European maritime-port cluster would further illuminate how institutional contexts shape regulatory implementation. The effective management of dangerous goods in an increasingly complex maritime environment will require professionals who are not only technically certified but continuously developed and institutionally supported.

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The Silent Side of Maritime Stress: Why Lonely Seafarers Withdraw

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Abstract: Stress in maritime settings is typically discussed through operational demands such as workload, fatigue, and organisational working conditions. However, the emotional dimension of seafarers' psychological experiences remains comparatively underexplored. This study examined emotional stressors, coping responses and their relevance for understanding the less visible dimension of maritime stress. The study was conducted on a sample of 117 seafarers across different ranks and vessel types. The analysis focused on indicators of emotional strain, including loneliness, social isolation, separation from family, and concern for family members, as well as coping strategies. Findings indicate that a substantial proportion of respondents reported emotional strain: loneliness was reported often or always by 47.9% of respondents, while separation from family was reported often or always by 76.1%. These emotional stressors were considered in relation to reported coping strategies. Rather than focusing only on pronounced externalised reactions, the study highlights less visible emotional burdens and how seafarers report coping with stress on board. Overall, the results suggest a "silent" dimension of maritime stress that may remain unrecognised within psychosocial risk assessment frameworks. The findings highlight the importance of integrating emotional and interpersonal components into seafarer support, including organisational, communication, and mentoring interventions.

Keywords: seafarers; emotional strain; loneliness; coping strategies; family separation

1. Introduction

Seafaring has long been recognised as a demanding occupation in which psychological strain emerges from the interaction of operational, organisational, environmental and social factors. Research on maritime stress has traditionally focused on workload, fatigue, long working hours, irregular sleep, safety risks and the physical demands of shipboard life. However, systematic evidence shows that seafarers' mental health is also shaped by less visible psychosocial conditions, including poor social support, low autonomy, weak team cohesion, perceived unsafety, scheduling uncertainty and prolonged periods at sea. These findings suggest that maritime stress cannot be understood only as a consequence of operational pressure; it also reflects the emotional and interpersonal conditions under which seafarers live and work (Brooks and Greenberg, 2022).

Among these less visible conditions, loneliness, social isolation and separation from family appear to be particularly important. Sampson and Ellis (2019) found that isolation, loneliness, lack of shore leave, fear of job loss and separation from family predispose seafarers to poor mental health. These factors are especially relevant because shipboard life combines work, residence and social life within the same confined environment, often for prolonged periods and with limited access to ordinary family and community support. In this context, emotional strain may remain silent and internalised, and may not necessarily be expressed through overt behavioural disruption or immediately visible distress.

The relevance of this emotional dimension becomes even more evident in periods of geopolitical disruption. The recent crisis in and around the Strait of Hormuz illustrates how quickly seafarers may become exposed to prolonged uncertainty, restricted mobility, fear, disrupted communication with families and concerns about supplies, salaries and repatriation. Reuters reported that more than 20,000 seafarers were stranded on around 2,000 vessels in the Gulf, with many facing shortages of food and water, isolation, fear and emotional distress (Reuters, 2026). Although the present study does not examine seafarers directly affected by the Strait

of Hormuz crisis, this context demonstrates the broader relevance of emotional stressors that may remain silent, internalised and difficult to detect in standard psychosocial risk assessments.

Against this background, the present study focuses on the silent and less visible side of maritime stress by examining emotional stressors and coping responses among seafarers. In particular, it investigates the reported burden of loneliness, social isolation, separation from family and concern for family members, and explores how seafarers report coping with stress while working on board. By shifting attention from externally visible operational stressors to emotional and interpersonal dimensions of shipboard life, the study aims to contribute to a more nuanced understanding of psychosocial risk in maritime work and to inform more targeted forms of seafarer support.

2. Emotional Stressors and Coping Responses in Seafaring

Emotional stressors in seafaring should not be understood only as private or individual experiences, but as part of the broader psychosocial risk environment in which seafarers live and work. Unlike fatigue, workload or acute operational stress, emotional strain may be less visible to colleagues, officers and shore-based management. A seafarer experiencing loneliness, social isolation or concern for family members may not necessarily display overt distress or disruptive behaviour. Instead, emotional burden may remain internalised and may be expressed through reduced communication, lower motivation to seek support, psychological distancing or less adaptive ways of coping with stress. This is particularly relevant in the shipboard environment, where work, rest and social life take place within the same confined setting and where opportunities for ordinary family and community support are limited.

Existing evidence supports the need to examine these less visible forms of psychosocial strain. Brooks and Greenberg (2022) identified poor social support, poor team cohesion, perceived unsafety, lack of autonomy, scheduling uncertainty and long duration at sea among the risk factors associated with poorer mental health and wellbeing among maritime personnel. Sampson and Ellis (2019) similarly emphasised isolation, loneliness, lack of shore leave, fear of job loss and separation from family as factors that may undermine seafarers' mental health and wellbeing. These findings indicate that emotional and interpersonal conditions are not secondary to maritime stress, but are central to understanding how seafarers experience and manage psychological pressure while on board.

Coping strategies are therefore important for understanding not only whether seafarers experience emotional strain, but also how they respond to it. Recent research on psychosocial burden and stress coping strategies among seafarers has highlighted the importance of examining harmful psychosocial factors together with coping responses (Szafran-Dobrowolska et al., 2023). In maritime settings, coping may include adaptive responses, such as physical activity, communication with family or friends and spending time outdoors, but also potentially less adaptive responses, such as increased smoking, use of medication, or increased consumption of alcohol and energy drinks. These responses should be interpreted within the specific conditions of life on board, where access to support, privacy, recreation and professional help may be limited.

For this reason, the present study examines emotional stressors such as loneliness, social isolation, separation from family and concern for family members in relation to coping responses reported by seafarers. This approach allows the analysis to move beyond the identification of stressors alone and to consider how emotional burden is managed in everyday shipboard life. By focusing on this less visible dimension of maritime stress, the study contributes to a broader understanding of psychosocial risk and may inform more sensitive forms of seafarer support, including communication, mentoring and organisational interventions.

3. Materials and Methods

3.1. Study design and participants

This study used a cross-sectional survey design to examine emotional stressors, coping responses and indicators of depression, anxiety and stress symptoms among seafarers. The sample consisted of 117 seafarers working across different ranks and vessel types. The survey included respondents with seafaring experience and was designed to capture psychosocial experiences related to shipboard life, with particular attention to emotional strain, family-related concerns and stress-coping responses.

The sample was predominantly male, reflecting the gender structure of the participating group. Respondents varied in age, years of maritime experience, rank and vessel type. The inclusion of seafarers from different occupational positions and vessel contexts allowed the study to explore emotional stressors across a heterogeneous maritime sample rather than within a single shipboard or company setting. The study was approved by the Ethics Committee of the Faculty of Maritime Studies, University of Split. Participation was voluntary and anonymous, and the data were analysed and reported only in aggregate form.

3.2. Measures

The questionnaire included demographic and occupational questions, indicators of maritime stressors, stress-coping responses and indicators of depression, anxiety and stress symptoms. Emotional stressors were assessed through items referring to social isolation and limited contact, separation from family, concern for family members and loneliness. Respondents rated how often these factors represented a source of burden while working on board, using a five-point response scale ranging from "never" to "always".

Coping responses were assessed by asking respondents how they usually try to relieve stress. Multiple responses were possible. The listed strategies included adaptive responses, such as regular exercise, talking with family or friends, spending time outdoors, focusing on positive aspects of life, participation in group activities and relaxation techniques, as well as potentially less adaptive responses, such as increased smoking, use of medication, increased consumption of alcohol or energy drinks, and other self-reported responses.

Indicators of depression, anxiety and stress symptoms were assessed using the 21-item Depression Anxiety Stress Scales questionnaire (DASS-21) (Lovibond and Lovibond, 1995). The DASS-21 includes three seven-item subscales measuring symptoms of depression, anxiety and stress. Subscale scores were calculated according to the standard scoring procedure, with higher scores indicating more pronounced symptoms on the respective subscale.

3.3. Data analysis

Descriptive statistics were used to summarise sample characteristics, emotional stressors, coping responses and DASS-21 indicators. Frequencies and percentages were calculated for categorical variables. For emotional stressors, the proportions of respondents reporting each stressor "often" or "always" were used to identify the most prominent sources of emotional burden.

Associations between emotional stressors and DASS-21 indicators of depression, anxiety and stress were examined using Spearman rank-order correlations, given the ordinal nature of the emotional stressor items. The analysis was exploratory and focused on identifying patterns of association rather than establishing causal relationships. All results are therefore interpreted as associations, not as evidence of causality or as differences between groups.

4. Results

4.1. Sample characteristics

The final sample consisted of 117 seafarers. Most respondents were male, with 115 men and 2 women. The mean age was 39.2 years, with ages ranging from 21 to 72 years. The median age was 37 years. Reported maritime experience ranged from 1 to 45 years, with a mean of 16.1 years and a median of 14 years.

The sample included seafarers from different ranks and vessel types. The most frequently represented vessel type was container ships, followed by passenger ships, bulk carriers, gas tankers and liquid cargo vessels. In terms of rank, the sample included captains, chief officers, second officers, chief engineers, second engineers, third officers, fourth engineers, electro-technical officers, cadets and other shipboard positions. At the time of the survey, 53 respondents were currently at sea, while 64 were not in active service on board.

4.2. Emotional stressors

The results show that emotional stressors were frequent among respondents. Separation from family and concern for family members were the most frequently reported sources of emotional burden, followed by loneliness and social isolation with limited contact. To distinguish stronger and more frequent burden from

broader exposure to emotional strain, Table 1 presents both the proportion of respondents reporting each stressor often or always and the proportion reporting it at least sometimes.

Table 1. Frequency of emotional stressors among seafarers (N = 117)

Emotional stressor	Often/Always, n (%)	At least sometimes, n (%)
Social isolation and limited contact	40 (34.2%)	68 (58.1%)
Separation from family	89 (76.1%)	105 (89.7%)
Concern for family members	71 (60.7%)	100 (85.5%)
Loneliness	56 (47.9%)	84 (71.8%)

When broader response categories were considered, the emotional burden became even more visible. Separation from family was reported at least sometimes by 89.7% of respondents, concern for family members by 85.5%, loneliness by 71.8%, and social isolation and limited contact by 58.1%. These findings indicate that the emotional dimension of maritime stress is not marginal, but forms a substantial part of the psychosocial burden experienced by seafarers.

4.3. Coping responses

Respondents reported a range of coping responses when dealing with stress. The most frequently selected strategies were regular exercise, reported by 48.7% of respondents, talking with family or friends, reported by 46.2%, spending time outdoors, reported by 41.0%, and focusing on positive aspects of life, reported by 35.0%. These responses suggest that many seafarers attempt to manage stress through behavioural activation, social communication and cognitive reframing.

At the same time, a smaller but relevant proportion of respondents reported potentially less adaptive coping responses. Increased smoking was reported by 20.5% of respondents, use of medication for calming, energy or sleep by 11.1%, and increased consumption of alcohol or energy drinks by 8.5%. Although these strategies were less frequent than adaptive coping responses, they are important because they may indicate attempts to regulate emotional strain in ways that could carry additional health risks if repeated or unsupported.

4.4. DASS-21 indicators and emotional stressors

DASS-21 subscale results showed that most respondents did not have elevated scores above the normal range, but a relevant proportion of the sample reported elevated symptom indicators. Scores above the normal range were found in 37.6% of respondents for depression, 40.2% for anxiety and 31.6% for stress. Moderate to extremely severe levels were observed in 29.1% for depression, 33.3% for anxiety and 24.8% for stress.

Emotional stressors were positively associated with DASS-21 indicators of depression, anxiety and stress. Social isolation and limited contact showed the strongest association with stress symptoms (rho = 0.498; $p < 0.001$), followed by depression (rho = 0.425; $p < 0.001$) and anxiety (rho = 0.380; $p < 0.001$). Loneliness was also associated with stress (rho = 0.431; $p < 0.001$), depression (rho = 0.400; $p < 0.001$) and anxiety (rho = 0.308; $p = 0.001$). Concern for family members showed positive associations with anxiety (rho = 0.327; $p < 0.001$), stress (rho = 0.323; $p < 0.001$) and depression (rho = 0.314; $p < 0.001$). Separation from family showed weaker but still positive associations with stress (rho = 0.289; $p = 0.002$), depression (rho = 0.239; $p = 0.009$) and anxiety (rho = 0.211; $p = 0.023$).

Taken together, these results suggest that the "silent" emotional dimension of maritime stress is associated with DASS-21 indicators of depression, anxiety and stress symptoms. The strongest pattern was observed for social isolation and loneliness, indicating that limited interpersonal contact and emotional disconnection may be particularly relevant for understanding stress, depression and anxiety symptoms among seafarers. These findings should be interpreted as associations and not as evidence of causality.

5. Discussion

The present study examined the less visible emotional dimension of maritime stress by focusing on loneliness, social isolation, separation from family, concern for family members and coping responses among seafarers. The findings show that emotional stressors were frequent in the sample. Separation from family was reported often or always by 76.1% of respondents, concern for family members by 60.7%, loneliness by 47.9%,

and social isolation with limited contact by 34.2%. These results support the central argument of the paper: maritime stress should not be understood only through fatigue, workload and operational demands, but also through emotional and interpersonal experiences that may remain less visible in everyday shipboard life.

Family-related stressors were the most frequently reported sources of emotional burden. Separation from family was reported at least sometimes by 89.7% of respondents, and concern for family members by 85.5%. This indicates that family separation is not only a background feature of seafaring, but a central psychosocial burden. These findings are consistent with previous research showing that isolation, loneliness, lack of shore leave, fear of job loss and separation from family may undermine seafarers' mental health and wellbeing (Sampson and Ellis, 2019). They also support broader systematic evidence that poor social support, weak team cohesion, low autonomy, scheduling uncertainty and prolonged periods at sea are relevant risk factors for poorer mental health among maritime personnel (Brooks and Greenberg, 2022).

The associations between emotional stressors and DASS-21 indicators further clarify this pattern. Social isolation and limited contact showed the strongest association with stress symptoms, while loneliness was also positively associated with stress, depression and anxiety indicators. Concern for family members and separation from family showed weaker, but still positive, associations with DASS-21 indicators. These findings suggest that emotional stressors are linked with symptoms of depression, anxiety and stress, especially when they involve limited interpersonal contact and loneliness. Since the study used a cross-sectional design, these results should be interpreted as associations, not as evidence of causality.

The coping results show that respondents used both supportive and potentially less adaptive strategies. Physical activity was reported by 48.7% of respondents, talking with family or friends by 46.2%, spending time outdoors by 41.0%, and focusing on positive aspects of life by 35.0%. These strategies may function as protective resources in an environment where access to professional support is limited. However, increased smoking was reported by 20.5% of respondents, use of medication by 11.1%, and increased consumption of alcohol or energy drinks by 8.5%. These responses indicate that some seafarers may regulate stress through strategies that could carry additional health risks if repeated or unsupported. This supports the view that psychosocial burden and coping responses should be examined together (Szafran-Dobrowolska et al., 2023).

A practical implication of these findings is that emotional strain may be underestimated in standard psychosocial risk assessments. Fatigue, working hours and operational safety are visible and measurable, whereas loneliness, concern for family members and reduced interpersonal connection may be less obvious to officers, colleagues and shore-based management. Although the present study did not examine seafarers directly affected by the Strait of Hormuz crisis, recent events in the Gulf illustrate how quickly separation, uncertainty and restricted communication may become central to seafarers' psychological experience (Reuters, 2026).

Seafarer support should therefore include emotional and interpersonal components, not only fatigue-related or operational interventions. Shipping companies, maritime education and training institutions and welfare organisations should strengthen communication with families, peer support, mentoring, psychological literacy and early recognition of distress. Mentoring systems and onboard communication practices may be particularly useful because they create safer opportunities for seafarers to express concern, seek support and remain connected with others.

Several limitations should be acknowledged. The study used a cross-sectional survey design, so causal conclusions cannot be drawn. The sample was heterogeneous but not representative of all seafarers or vessel types. The data were self-reported and may be affected by recall, social desirability or willingness to disclose psychological difficulties. Future research should examine emotional stressors and coping patterns longitudinally, include larger and more diverse samples, and explore how organisational support, onboard communication and family contact influence the relationship between emotional strain and DASS-21 indicators.

6. Conclusion and Recommendations

This study highlights the silent and less visible side of maritime stress. Emotional stressors were frequent among respondents, particularly separation from family, concern for family members, loneliness and social isolation. These stressors were positively associated with DASS-21 indicators of depression, anxiety and stress, with the strongest pattern observed for social isolation, limited contact and loneliness. The findings suggest that emotional and interpersonal dimensions are not secondary to maritime stress, but form part of seafarers' psychosocial risk environment.

The results also show that seafarers use both supportive and potentially less adaptive coping responses. Physical activity, communication with family or friends and spending time outdoors were the most frequently reported coping strategies, while a smaller proportion of respondents reported increased smoking, use of medication or increased consumption of alcohol and energy drinks. This indicates the need to strengthen supportive coping resources and reduce reliance on potentially harmful strategies.

Based on the findings, psychosocial risk assessment in maritime settings should include emotional stressors such as loneliness, social isolation, separation from family and concern for family members. Shipping companies should support regular and meaningful communication between seafarers and their families. Maritime education and training institutions should include emotional literacy, coping skills, peer support and help-seeking behaviour in seafarer education. Mentoring and onboard support systems should also be developed to help identify emotional strain before it affects wellbeing, interpersonal relations or safety.

Overall, protecting seafarers' wellbeing requires more than managing fatigue and workload. It also requires recognising the emotional realities of life at sea and developing organisational, educational and interpersonal support that makes the silent side of maritime stress more visible and more effectively addressed.

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A Qualitative Analysis of Affective Learning Outcomes in Marine Transportation Curriculum

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Abstract: Despite increasing recognition of the affective domain in education, Maritime Education and Training (MET) institutions continue to prioritize cognitive and psychomotor domains while overlooking affective learning outcomes. This study examined the extent to which affective learning outcomes are included in the Bachelor of Science in Marine Transportation (BSMT) curriculum of a MET institution in the Philippines. A qualitative dual-stage design was employed. First, document analysis was conducted on 36 deck course manuals using the affective taxonomy of Krathwohl et al. (1964). Second, semi-structured interviews were conducted with three curriculum developers, including the Instructional Development Office coordinator to identify barriers and possible inclusion points for affective pedagogy. Findings revealed that none of the course manuals contain explicit affective learning outcomes. Interview data show that the main barrier is the "alignment trap", wherein curriculum developers relied heavily on national minimum standards and STCW-mandated technical competencies, leaving little room for affective learning outcomes integration. Despite this, participants identified several maritime courses where affective learning outcomes could be embedded. The study concludes that the absence of affective learning outcomes stems from systemic regulatory limitations rather than professional indifference. It recommends revisiting the Administration and STCW standards to explicitly include affective competencies in MET curricula.

Keywords: Affective domain; affective learning outcome; maritime education and training

1. Introduction

The teaching and learning process ideally encompasses three domains - cognitive, affective, and psychomotor. In planning for the lessons, course developers and instructors include these three domains in their formulation of outcome statements to make sure that all learning areas of the students are addressed and/or holistically developed thereby they eventually possess "a wide range of knowledge, skills and attitudes" (Subedi, 2022, p.54), and emotional and social competencies (Mohamad, 2025) that meet the requirements of the current job markets (Mahfuzah, AhmadFakhrurrazi, and Norhapizah, 2022).

While education aims for the holistic development of the learners, researchers posited that higher education institutions focus mainly on studying the cognitive domain and underemphasize the affective domain (Mukherjee and Kittur, 2025; Potgieter, Filmalter, and Maree, 2025; Winters, 2025). Moreover, there is a lack of integrated research on the affective factors that may have an effect on the academic performance of students (Kobicheva, Tokareva, and Baranova, 2022). Furthermore, less attention is given to the affective domain in the design of the curriculum and the delivery of instructions (Dorji and Yangzom, 2021). These result in lack of empirical evidence on the attainment of the affective outcomes, and the gap in ensuring that students are comprehensively educated.

Together with the increasing advancements in Maritime Education and Training (MET), the significance of the affective domain – the realm of feelings, emotions, attitudes, interests, degrees of acceptance or rejection, and values, ethics and emotional competencies (Potgieter, Filmalter, and Maree, 2025), has been recognized and explored as a research area. However, MET institutions (METI) continue to prioritize cognitive and psychomotor domains, leaving a critical gap in developing affective dispositions as part of the overall competence of seafarers. To somehow fill the affective development gap, this study investigates the extent to which affective learning outcomes are included in the Bachelor of Science in Marine Transportation (BSMT)

curriculum in a MET institution in the Philippines, and recommend possible ways on how this vital area of learning may be addressed.

The results of this study provide empirical data on the inclusion of affective learning outcomes in the courses in maritime programs, specifically the marine transportation program. The shipping business has slowly recognized the importance of the affective competence of seafarers. This shift entails a move in heavy focus on theoretical and practical competence to desirable values, attitudes and behaviors of future global maritime professionals. Moreover, the study may inform the Maritime Industry Authority (MARINA), the Administration in the Philippines, and the shipping companies of their heavy reliance on the development of theoretical and practical skills among maritime students. The management level down to the course developers of the MET Institutions may use the data of this study as their reference in the improvement of their curriculum design.

The Three Domains of Learning

Theoretically, the three domains of learning have to be addressed in order for a learner to develop holistically. The seminal work of Bloom et al. (1956) in taxonomy of educational objectives identified the three learning domains which are the cognitive, affective and psychomotor. The cognitive domain focuses on the development of mental processes required of the students to reason, solve problems and apply knowledge (Mukherjee and Kittur, 2025). It has the following dimensions: remember, understand, apply, analyze, evaluate and create (Anderson et al., 2001). The affective domain, anchored in the work of Krathwohl et al. (1964), addresses the emotions, feelings, attitudes, and values of learners using the following levels of taxonomies: receiving, responding, valuing, organizing and internalizing (characterization). Lastly, the psychomotor domain involves the development of bodily movements that demonstrate knowledge (Anand et al., 2024) in the following progressive taxonomy: perception (awareness), set, guided response, mechanism, complex overt response, adaptation and origination (Simpson, 1972).

STCW and BoK Competences/Outcomes

In the competency mapping done by the MARINA in 2018, competencies like assertiveness and leadership, and consideration of team experiences, which were directly taken from the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) Including 2010 Manila Amendments (International Maritime Organization, 2017), are included. These competencies are not exclusively affective, though affective learning substantially influences their development and expression. The standard assessment of these areas, especially in the affective domain, is the problem since the indication of the use of rubrics is vague and may be interpreted in different ways. In the source itself, the criteria for evaluating competence seem to lean closer still to the cognitive and practical aspects. Similarly, the International Association of Maritime Universities (2019), in their Global Maritime Professional (GMP) Body of Knowledge (BoK), formulated intended learning outcomes in the affective domain. However, some of the statements do not have guidance to develop clear standards of measurement.

The Affective Domain of Learning

The development of affective competencies in students is imperative in any field. For instance, Al-Hassan et al. (2026) highlighted the importance of the affective domain in developing empathy, emotional intelligence, and professional commitment among nursing students. Kou et al. (2024) also highlighted the roles of the integration of the three domains in optimizing learning outcomes.

A number of studies have found that the affective domain of learning is not included or underemphasized in the teaching-learning process in higher education. Mukherjee and Kittur (2025) surveyed engineering students and found that the respondents are confident in the requirements of the cognitive domain while needing more engagement in the affective and psychomotor domains. Meanwhile, a structured interview and a systematic literature review of Dorji and Yangzom (2021) revealed that college curricula and educators did not focus much on the affective domain of learning. Mahfuzah, AhmadFakhrurrazi and Norhapizah (2022) also posited that the imbalance between the three domains was brought about by the Industrial Revolution 4.0, which focused so much on equipping students with workforce cognitive and psychomotor skills to be at par with the technological advancements of the 21st century.

Considering the aforementioned context, this paper analyzes the manuals for the major courses in the Bachelor of Science in Marine Transportation program to check for explicit inclusion of affective learning outcomes. The specific objectives are the following:

- Describe the explicit inclusion of affective learning outcomes in the course manuals;
- Determine the challenges in the inclusion of affective learning outcomes in the course manuals;
- Identify courses where explicit affective learning outcomes may be included.

As the need to address the affective domain in MET is gaining popularity, the results of this study can greatly contribute to the improvement of the course packages of the maritime institution involved in this study and other stakeholders of the maritime industry.

2. Materials and Methods

This study employed the qualitative dual-stage design, where the researchers first conducted a document analysis of the manuals of all the major marine transportation program courses (36) of a METI in the Philippines to determine the presence of explicit affective learning outcomes based on the taxonomy developed by Krathwohl et al. (1964). The focus of identification was the course and the learning outcomes statements written in the different course manuals. These statements were found in the different parts of the manual: Part A (Course Specifications), Part B (Course Outline), Part C (Basic Teaching Syllabus), and Part D (Detailed Teaching Syllabus). After the document analysis, they interviewed the three course developers from the Instructional Development Office to determine the challenges in the inclusion of affective learning outcomes in the course manuals, and to identify courses where explicit affective learning outcomes may be included. Follow-up interviews were also conducted to seek clarifications to some findings.

Before doing the document analysis and the interview, the researchers asked permission from the Instructional Development Coordinator and the course developers. The interviewees were informed of the objectives of the study and the reasons for the interview. The researchers assured the persons involved of the confidentiality of the information gathered, the anonymity of their identity, and the use of all data for research purposes only.

For the document analysis, the Instructional Development Coordinator shared with the researchers the access to the marine transportation course manuals. These manuals were read at least twice by the researchers to look for explicitly stated learning outcomes, course outcome and intended learning outcomes statements, for the affective domain using Krathwohl's taxonomy. After their individual reading, the researchers compared their findings.

The recorded interviews were transcribed and initially read by the researchers for a general grasp of the ideas expressed by the participants. The answers of the interviewees were coded and categorized in reference to the research questions of the study.

3. Findings and Analysis

Based on the document analysis and the interviews conducted, the following are the findings of the researchers:

3.1 Non-inclusion of Affective Learning Outcomes in the Course Manuals

The results of document analysis revealed that all the course manuals of the marine transportation program have no explicit inclusion of affective learning outcomes. This was confirmed by the course developers during the interview. When asked why this was the case, they gave a number of reasons. One, their course development was solely based on the course packages prepared by the Joint Commission on Higher Education (CHED) - MARINA, which only contain cognitive and psychomotor learning outcomes. These packages, supposedly based primarily on the STCW, are handed down to different METIs to substantiate then implement. The course developers of the METI specifically develop the Part D of the course manual. This part, Detailed Teaching Syllabus, contains the course descriptive title, STCW Competence, credit units, lecture/laboratory hours, prerequisite, course description, course outcome statement/s, revision history, and the main part, which is divided into six columns (learning outcomes; assessment; topic; teaching-learning activity; equipment, materials, and references; and the indicative hours). All the contents in this part are based on the course and

learning outcome statements formulated by CHED-MARINA, which provide the regulatory mechanism that requires mandatory adoption. The rigidity of the framework, containing many outcome statements which are cognitive and psychomotor, is another reason given by the course developers, leaving little room for institutional customization, including the addition of affective outcome statements. Finally, the course developers reasoned out that even if there was space for the addition of affective outcome statements, there was no instruction from the management to include such, indicating a strong priority on policy alignment over curriculum innovation. When suggested that the Body of Knowledge has affective learning outcome statements that they can adopt in their course development, one of the course developers said, "*The procedure manual does not dictate us to create a third course manual to address the Body of Knowledge.*" This shows that their work is tied to regulatory and institutional requirements.

3.2 Challenges in the Inclusion of Affective Learning Outcomes in the Course Manuals

The interview with the course developers revealed some challenges in the inclusion of affective learning outcomes in the course manuals used in the marine transportation program. One, the developers admitted that they lack a good understanding of the affective domain concept. This may be due to pervasive terminology and taxonomy ambiguity, wherein one primary source of confusion is the conceptual overlap between affective domain and soft skills. Moreover, course developers also demonstrated uncertainty about how to organize affective domain taxonomies. This first challenge resulted in related issues, which are the challenges of assessment and teaching-learning activities (TLA). Given the room to integrate the affective domain, the inherent challenges of assessment constrain the developers to design the course manual to contain the appropriate assessment methods with appropriate assessment criteria. One of the developers inquisitively asked during the interview, [How will you measure it in the assessment… How will you grade it?]" indicating a challenge in designing meaningful assessment tasks. Relatedly, the challenge of TLA appropriate to the learning outcome/s to be integrated was mentioned. Next, the little room left for institutional customization limits the ability to implement new courses or curriculum innovation, with students already operating at near full capacity with only minimal vacant hours available.

3.3 Courses Where Affective Learning Outcomes May Be Included

As mentioned, given the tightly regulated framework from CHED-MARINA, the course developers still identified the potential courses where the affective domain can be included. One course developer had an inclusive perception on the inclusion of affective learning outcomes when he said that with good design, learning outcomes under the affective domain may be included in all the courses. He added that a graduate has to be holistically developed so it is imperative that all the domains of learning are addressed. The other course developer was cautious, however as he commented, "I think not because for example… we have courses that are focused solely on technical or for me, for now, we should look at the evaluation criteria first to check if there are criteria for the affective domain because if STCW focuses only on the theoretical or practical, then you are limited there." He was of the opinion that the criteria in assessment be reviewed first so areas of inclusion may be identified. Aside from this, he suggested focusing and working within the competences required in the STCW. Notwithstanding their differences, they both agree that learning outcomes in the affective domain may be formulated for the courses Deck Watchkeeping 2 and Management.

4. Discussion

This paper has established that affective learning outcomes are not included in the course manuals of the marine transportation program. This non-inclusion reflects both systemic and institutional constraints. Course developers rely heavily on the CHED-MARINA course packages, which are themselves derived from the STCW. Since these packages emphasize cognitive and psychomotor domains, developers are left with little flexibility to incorporate affective outcomes. These curricular and development constraints are also observed in other higher education institution programs as determined by Mukherjee and Kittur (2025), Dorji and Yangzom (2021), and Kou et al. (2024). Almuzani et al. (2026) also highlighted barriers in the integration including the lack of prescribed assessment formats in the affective domain by certification authority.

The challenges identified further complicate the integration of affective learning into the different courses. Developers admitted to limited understanding of the affective domain, often conflating it with soft skills. This conceptual ambiguity, coupled with uncertainty about taxonomy organization, hinders their ability to design

meaningful outcomes. More importantly, the inherent difficulty of assessing affective learning outcomes was emphasized. The question of one of the developers about how to assess affective learning outcomes imply a challenge in operationalizing affective learning outcomes in measurable terms. This necessitates workshops on assessment strategies that may address the affective learning outcomes. Additionally, different strategies should also be introduced and explored in order to address the lack of available teaching-learning activities and minimal room for institutional customization. While applied in other fields, the strategies mentioned by He, Hamid and Nor (2025), and Potgieter, Filmalter, and Maree (2025) like simulations, reflective journaling, storytelling and cooperative/collaborative activities may be considered as starting points.

The potential inclusion of affective outcomes in the course manuals presented two differing views of the course developers. One developer expressed integration across all courses, as he believed that graduates must be developed in all domains of learning. This view aligns with contemporary educational philosophies that emphasize the importance of values, attitudes, and interpersonal skills in professional competence. The other developer, however, was more cautious as he suggested that inclusion should be referenced to the evaluation criteria within STCW competencies. This divergence reflects a tension between aspirational curriculum design and pragmatic adherence to regulatory standards.

Nevertheless, consensus emerged around the possibility of embedding affective outcomes in specific courses such as Deck Watchkeeping 2 and Management, where interpersonal skills, responsibility, and leadership are integral to competence. These courses provide natural entry points for affective learning, as they involve decision-making, teamwork, and ethical responsibility, wherein attitudes and values are as critical as technical proficiency.

The small number of interviewees, the three course developers, may have represented the whole institution but may not be able to generalize the situation of all the maritime schools in the country. The developed course manuals undergo reviews and validation by experts prior to implementation; however, the process and the result may be applicable to the institution only. This calls for a wider scope of another study in order to validate the findings of this present study.

Overall, the discussion reveals that while regulatory frameworks and institutional priorities currently limit the inclusion of affective learning outcomes, there is recognition among course developers of their importance. The challenge lies in bridging conceptual understanding, assessment design, and regulatory compliance. Addressing these issues could pave the way for a more holistic curriculum that develops not only technical competence but also the values and attitudes essential for maritime professionals.

5. Conclusions and Recommendations

Based on the findings presented in this study, the exclusion of affective learning outcomes in the course manuals of the marine transportation program rooted from institutional and national and international regulatory constraints. The holistic development of marine transportation cadets is imperative, but challenges need to be hurdled in order for the inclusion of affective learning outcomes to be made possible.

The issues in the inclusion of affective learning outcomes in the course manuals of the marine transportation program may be addressed when the STCW revision become more explicit in the affective competencies required of maritime program graduates. Going further, the MARINA may consider doing some revisions in the required competencies and accommodate the appropriate and relevant affective learning outcomes for the program. In METIs, the course developers may have to attend seminar-workshops on the affective domain to clarify their confusion of the affective domain with the soft skills, and to train them to develop affective learning outcomes assessment. Later, they may consider adding affective learning outcomes in the courses they are developing for pilot testing. They may start with Deck Watchkeeping 2 and Management courses as these courses involve responsibility, interpersonal skills, and leadership. This top-down approach stems from the determined reason for the exclusion of affective learning outcomes, and that is the emphasis of cognitive and psychomotor domains, leaving no to little room for addition of the affective domain.

Because this study focused on marine transportation courses only, the proponents recommend that other researchers focus on the general education and/or marine engineering courses for comparative purposes and general appraisal of the inclusion of affective learning outcomes in the maritime curriculum. Also, the methods used by this present study may be expanded to cover areas that may enrich contextual and conceptual

understanding of the area of study. Classroom observations and interviews with instructors and students may be carried out to widen the area of analysis and yield a more comprehensive discussion.

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From Abandonment to Key Workers: The Impact of the 2014–2025 MLC Amendments on Seafarers' Labour Rights

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Abstract: The Maritime Labour Convention, 2006 (MLC) is the key international document governing seafarers' labour-law status, as it consolidates minimum standards for seafarers' working and living conditions within a single document and links them to a supervision and enforcement framework tailored to maritime administrations and operational practice. For the purposes of this paper, the MLC amendment mechanism is of central importance. While the Articles and Regulations may be amended only at an ILO international conference pursuant to Article 19 of the ILO Constitution and Article XIV of the MLC, the Code may be amended through the simplified procedure under Article XV of the Convention, without a renewed ratification process of the kind required for amendments to the Articles and Regulations. Since its entry into force, the MLC Code has been amended five times, enabling targeted updates where practice reveals shortcomings in protection. This paper provides an individual analysis of each set of amendments to the MLC Code to date and proposes de lege ferenda solutions aimed at further strengthening the MLC's protective mechanisms.

Keywords: MLC 2006; Article XV Code amendments; abandonment; on-board complaints; key workers

1. Introduction

The Maritime Labour Convention, 2006 (hereinafter: MLC) constitutes the core international document for the protection of labour at sea, as it consolidates minimum standards for seafarers' working and living conditions within a single document and links them to supervision and enforcement mechanisms tailored to maritime administrations and operational practice. In Croatian scholarship, the MLC is commonly described as a consolidation and modernisation of earlier International Labour Organization standards (hereinafter: ILO), with its practical value being particularly evident in flag State obligations and in the possibility of port State inspection (Petrinović and Lovrić, 2015).

For the purposes of this paper, the MLC's structural feature embedded in its amendment mechanism is decisive. While the Articles and Regulations may be amended only at an international conference pursuant to Article 19 of the ILO Constitution and Article XIV of the MLC, the Code may be amended through the simplified procedure set out in Article XV of the Convention. Since the Code serves to elaborate the application of the Regulations in greater detail, amendments to the Code must remain within the general framework of the Articles and Regulations; it is precisely through this mechanism that the standards may be continuously adjusted to recurring risks of violations of seafarers' labour rights (Vuković, 2025).

Between 2014 and 2025, the MLC Code was amended five times. These amendments cannot be regarded as isolated technical updates; rather, they represent a gradual strengthening of seafarers' labour-rights protection in areas where practical gaps most frequently arose. The first amendments, adopted in 2014, were already directed at strengthening remedies (direct action) and the enforceability of core claims, as they introduced mandatory financial security for abandoned seafarers and for certain contractual claims related to death or long-term disability, thereby enhancing the minimum enforceability of fundamental claims in international employment relationships at sea (Vuković et al., 2024).

The aim of this paper is to conduct a doctrinal legal analysis and to present and classify, in a systematic manner, the amendments to the MLC Code adopted in 2014, 2016, 2018, 2022 and 2025, and to assess their cumulative effect on the practical protection of seafarers' labour rights.

2. Normative framework and the MLC amendment mechanism

MLC was adopted in February 2006 under the auspices of the ILO as the result of a tripartite agreement between governments, seafarers' trade unions and shipowners' representatives. In order to ensure that the new Convention would be as effective as possible, and taking into account the shortcomings of the previous approach to the adoption of Conventions and Recommendations, the drafters of the MLC introduced several innovations. One of them concerns the very structure of the MLC. Within the ILO, it is customary to separate binding norms from non-binding ones, so that the text of a Convention is accompanied by Recommendations. However, since the IMO also participated in the preparation of the MLC, the Convention was structured in a manner similar to the approach used by the IMO for its international conventions, meaning that binding provisions and recommendations are brought together within a single document (Petrinović et al., 2021).

Accordingly, the MLC consists of the Preamble, Articles, Regulations and the Code. Fundamental principles and obligations of Member States are contained in the Articles and Regulations, while the detailed provisions relating to the application of the Regulations are set out in the Code. Part A of the Code (Standards) is mandatory, whereas Part B (Guidelines) contains recommendations that Member States should give due consideration to when adopting national legislation implementing the MLC. The Regulations and the Code are divided into five Titles. Title 1, *Minimum requirements for seafarers to work on a ship*, contains provisions on the minimum age, medical certification, qualifications of seafarers and recruitment and placement. Title 2, *Conditions of employment*, sets out requirements concerning the seafarers' employment agreement, wages, hours of work and hours of rest, compensation in the event of a ship's loss or foundering, manning levels and repatriation. Title 3, *Accommodation, recreational facilities, food and catering*, prescribes standards for accommodation and recreational facilities on board, as well as the quality of food and arrangements for catering. Title 4, *Health protection, medical care, welfare and social security protection*, addresses health protection and medical care, welfare measures, social protection and shipowners' liability for the consequences of illness or occupational injury. Finally, Title 5, *Compliance and enforcement, sets out provisions on the responsibilities of the flag State, the port State and labour-supplying States* (Vuković et al., 2024).

It is also important to note Article XIII of the MLC, which provides for the establishment of the Special Tripartite Committee (hereinafter: STC), tasked with keeping the provisions of the MLC under continuous review and, where appropriate, proposing amendments. For the purposes of this paper, it is essential to distinguish between amendments to the Convention as a whole and amendments to the Code. The Articles and Regulations may be amended only at an international conference pursuant to Article 19 of the ILO Constitution, whereas the Code may be amended through the simplified procedure provided for in Article XV of the Convention. This simplified mechanism for amending the Code enables the MLC to be continuously adapted to new requirements and challenges in the maritime industry (Vuković, 2025).

3. Amendments to the MLC code (2014-2025)

In this chapter, the amendments to the MLC Code are presented chronologically, with a focus on their legal function in the protection of seafarers' labour rights. The starting point is that the effectiveness of the Code is not measured by the number of new provisions, but by whether it strengthens the mechanisms that enable seafarers to realise their labour rights in practice.

3.1. The 2014 Amendments: Mandatory Financial Security

The amendments adopted in June 2014, which entered into force in January 2017, focus on financial security as a key precondition for the practical enforceability of seafarers' core labour rights, in particular in cases of abandonment and in cases of death or long-term disability. They address the practical problem that financial security in the original text of the MLC was formulated too broadly and without sufficient precision, which raised a number of legal issues, including the legal nature of the security arrangement, proof of its existence, and direct access to the provider of financial security (Petrinović and Lovrić, 2017).

In the area of repatriation, the former Standard A2.5 is renumbered as Standard A2.5.1, and a new Standard A2.5.2 (Financial security) is introduced, setting requirements for an expeditious and effective financial security system to assist seafarers in cases of abandonment. A seafarer is deemed to be abandoned where the shipowner fails to cover the cost of repatriation, leaves the seafarer without the necessary maintenance and support, or otherwise unilaterally severs ties with the seafarer, including by failing to pay contractual wages for at least two

months. The Member must ensure that ships flying its flag are covered by a financial security system meeting the requirements of Standard A2.5.2. Such a system may take the form of social security, insurance, a national fund or similar arrangements, but it must provide direct access, adequate cover and expeditious financial assistance to each abandoned seafarer (Petrinović and Lovrić, 2017).

The amendments further specify the content of protection. "Necessary maintenance and support" include adequate food, accommodation, drinking water supply, fuel necessary for survival on board and necessary medical care. Assistance is to be provided promptly upon request by the seafarer or the seafarer's designated representative, and Guideline B2.5.3 emphasises that verification of elements of a claim must not prevent the seafarer from immediately receiving the part of the assistance that has already been recognised as justified. Assistance must be sufficient to cover outstanding wages and other entitlements due (limited to four months), reasonable expenses including repatriation, and the seafarer's basic needs until arrival at the destination (MLC, 2024).

The enforcement dimension is equally important. Ships to which the MLC certification regime applies—i.e., ships of 500 GT or over engaged in international voyages—must carry on board two documents evidencing financial security, namely for: (i) claims in cases of abandonment (outstanding wages, repatriation and basic needs), pursuant to Standard A2.5.2 and Appendix A2-I; and (ii) contractual claims related to the death or long-term disability of a seafarer, pursuant to Standard A4.2.2 and Appendix A4-I. These documents must be issued by the provider of financial security, and a copy must be posted in a conspicuous place on board accessible to seafarers. Since the evidence must be available on board and accessible to seafarers, its verification is also practically possible within port State inspection (Petrinović and Lovrić, 2017).

Within the shipowners' liability framework (Regulation 4.2), the 2014 amendments introduce a parallel financial security logic for contractual claims related to death or long-term disability. Standard A4.2 is renumbered as Standard A4.2.1, and a new Standard A4.2.2 (Treatment of contractual claims) is introduced, defining a contractual claim as a claim relating to death or long-term disability due to an occupational injury, illness or hazard, as provided for under national law, the seafarers' employment agreement or a collective agreement. Financial security may also take different forms here, such as social security, insurance, a national fund or similar arrangements (Petrinović and Lovrić, 2015).

In practice, however, shipowners most commonly meet the financial security requirement by entering the ship with a P&I club, with clubs within the International Group of P&I Clubs aligning their rules and extending cover to include liabilities arising under the MLC (Petrinović and Lovrić, 2017).

3.2. The 2016 Amendments: Shipboard Harassment and Bullying

The amendments adopted in June 2016, which entered into force in January 2019, address shipboard harassment and bullying and expressly place it within the field of occupational safety and health (hereinafter: OSH). Their legal significance lies in confirming that the protection of seafarers' labour rights is not confined to classical elements of the employment relationship—such as wages, hours of work and the seafarers' employment agreement—but also extends to the working environment in which those rights are exercised.

In the Code, under Regulation 4.3, the amendments are implemented through changes to Guideline B4.3.1, which requires that, in taking measures, due account be taken of the most recent version of the document Guidance on eliminating shipboard harassment and bullying, jointly published by the International Chamber of Shipping and the International Transport Workers' Federation. The same Guideline introduces shipboard harassment and bullying as a specific matter that Members should take into consideration in national OSH measures. In addition, Guideline B4.3.6 is amended to require that investigations also consider problems arising from shipboard harassment and bullying, thereby emphasising the preventive and investigative dimension of protection (MLC, 2016).

Alongside these substantive changes, the 2016 amendments introduce a targeted measure in the area of certification. Standard A5.1.3 is supplemented so that, following a renewal inspection completed before the expiry of the Maritime Labour Certificate, the validity of the existing certificate may be extended for up to five months where compliance has been confirmed, but the new certificate cannot immediately be issued and made available on board. Appendix A5-II is amended accordingly by adding a box for recording such an extension. This avoids a formal gap in documentary proof of compliance during the transitional period, without altering the material standards of protection (Yilmaz, 2025).

3.3. The 2018 Amendments: Piracy and Armed Robbery against Ships—Continuity of Fundamental Rights during Captivity

The amendments to the MLC Code approved in June 2018, which entered into force in December 2020, address situations in which a seafarer is held captive on or off the ship as a result of piracy or armed robbery against ships. Their legal purpose is to ensure that fundamental rights arising from the employment relationship do not lapse due to the expiry of the agreed period or a formal termination notice in circumstances where the seafarer is objectively unable to influence the course of the employment relationship.

First, Standard A2.1 (Seafarers' employment agreements) is supplemented by a new paragraph 7 providing that the seafarers' employment agreement continues to have effect for the entire period of captivity, regardless of whether the agreed term has expired or a notice of suspension or termination has been given. The same paragraph also introduces definitional references. For "piracy", reference is made to the United Nations Convention on the Law of the Sea, while "armed robbery against ships" is defined as any unlawful act of violence or detention, or any act of depredation (or threat thereof), committed for private ends against a ship or against persons or property on board such a ship, within a State's internal waters, archipelagic waters and territorial sea, including inciting or intentionally facilitating such an act (MLC, 2018).

Second, Standard A2.2 (Wages) is supplemented by a new paragraph 7 providing that, in cases of captivity as a result of piracy or armed robbery against ships, wages and other entitlements under the seafarers' employment agreement, the relevant collective agreement or applicable national law continue to be paid for the entire period of captivity, as well as for the period until release and repatriation in accordance with Standard A2.5.1. Where a seafarer dies during captivity, payment continues until the date of death as determined under the applicable national law (MLC, 2018).

Third, Guideline B2.5.1 (Entitlement to repatriation) is amended so that captivity as a result of piracy or armed robbery against ships is excluded from the exception relating to the time-bar/interruption of the entitlement to repatriation; accordingly, the entitlement to repatriation cannot cease due to an untimely request while the seafarer remains in such a status (Yilmaz, 2025).

3.4. The 2022 Amendments: Practical Effectiveness of Protection in Exceptional Circumstances

The amendments adopted in June 2022, which entered into force in December 2024, address issues that became particularly evident in practice during the COVID-19 pandemic, when the enjoyment of seafarers' fundamental rights was often contingent upon the possibility of disembarkation, access to shore-based medical care, repatriation, and the maintenance of minimum living conditions on board in prolonged exceptional circumstances (Yilmaz, 2025).

These amendments are distributed across several areas of the Code. Under Standard A1.4, a requirement is introduced to establish a system of protection, through insurance or other appropriate measures, under which seafarers are compensated for monetary loss arising from a failure of the recruitment and placement service or the shipowner to meet obligations under the seafarers' employment agreement, together with an obligation to inform seafarers of their rights under that system. In the area of repatriation, Standard A2.5.1 is supplemented by a new paragraph requiring Members to facilitate the prompt repatriation of seafarers, including in situations where a seafarer is deemed to be abandoned within the meaning of Standard A2.5.2, while also emphasising the need for cooperation between the port State, the flag State and labour-supplying States so that replacement seafarers are recognised as having the rights and entitlements provided for under the Convention (MLC, 2022).

The 2022 amendments also reinforce the preconditions for adequate living conditions on board in circumstances of prolonged service at sea. Standard A3.1 is supplemented to require that recreational facilities and services on board include social, and Guideline B3.1.11 further emphasises reasonable access to ship-to-shore communications. The amendments thus introduce an obligation on shipowners, as far as is reasonably practicable, to provide access to the internet on board. Standard A3.2 further specifies requirements relating to food and drinking water, stressing adequacy in terms of quantity, nutritional value, quality and variety, and requires that food and drinking water be provided free of charge for the entire period during which the seafarer is on board and in service (MLC, 2022).

Particularly important are the additions in the field of medical care and safety. Standard A4.1 introduces an obligation on the Member to ensure the prompt disembarkation of seafarers requiring urgent medical care and access to shore-based medical facilities for appropriate treatment, together with provisions facilitating the

repatriation of a seafarer's body or ashes in accordance with the seafarer's wishes or the wishes of the next of kin (MLC, 2022).

Finally, in the area of occupational safety and health, Standard A4.3 is supplemented by an emphasis on personal protective equipment and measures to reduce exposure to harmful environmental factors and chemicals, and introduces an obligation for adequate investigation, recording and annual reporting of seafarer fatalities and publication in a global register, together with specification of the minimum data elements to be included in such reports (MLC, 2022).

3.5. The 2025 Amendments: Facilitating Seafarers' Mobility, Shore Leave and Strengthening Procedural Safeguards

The amendments adopted in 2025, agreed at the fifth meeting of the STC in Geneva in April 2025, will enter into force in December 2027. They focus on repatriation, shore leave, the designation of seafarers as key workers, and the strengthening of protection against violence and harassment, together with additional procedural safeguards in on-board complaints procedures (ILO, 2025).

In the area of repatriation, Standard A2.5.1 is supplemented so as to require Members to facilitate the repatriation of seafarers without discrimination on any ground and irrespective of the flag of the ship on which they are employed (MLC, 2025).

Within the framework of leave, a new Standard A2.4.2 on shore leave is introduced. Port State authorities are required to allow seafarers shore leave after completion of formalities, unless there are grounds for refusal related to public health, public safety, protection or public order. At the same time, shipowners are required, for the health and well-being of seafarers, to organise and facilitate shore leave to the extent compatible with the operational requirements of the ship (MLC, 2025).

Furthermore, in order to facilitate seafarers' movement in connection with employment, Guideline B2.5 is supplemented by the introduction of Guideline B2.5.2 on key workers. Members are recommended to designate and recognise seafarers as key workers and to take appropriate measures to facilitate their safe movement in connection with employment, including, inter alia, shore leave, repatriation, crew changes and access to shore-based healthcare (MLC, 2025).

Of particular significance is the strengthening of protection against violence and harassment on board. Guideline B1.4.1 (Recruitment and placement) introduces measures to prevent and address violence and harassment in recruitment and placement processes, including sexual harassment, bullying and sexual assault, while Guideline B3.1.10 (Accommodation and recreational facilities) adds a requirement for the availability of suitable and sufficient menstrual hygiene products and appropriate means of disposal. Standard A4.3 establishes an obligation to prevent and combat violence and harassment on board. To that end, it requires that violence and harassment be prohibited in national legislation and that the relevant concepts be clearly defined, taking into account the Violence and Harassment Convention, 2019 (No. 190) (MLC, 2025).

Finally, in the area of on-board complaints procedures (Standard A5.1.5), procedural safeguards are strengthened. The right of a seafarer to bring a complaint directly to the master is confirmed and, where necessary, to the appropriate shore-based authority. Protection against victimisation is extended to complainants, victims, witnesses and whistleblowers, with victimisation linked to any adverse action taken against a seafarer because of a complaint that is not manifestly vexatious or malicious (MLC, 2025).

4. Conclusion

The MLC is the most important and comprehensive multilateral international treaty governing seafarers' employment relationships. For the purposes of this paper, the simplified mechanism for amending and further improving its provisions under Article XV of the MLC is of particular importance.

To date, the MLC Code has been amended five times through this simplified procedure. The 2014 amendments occupy a central place, as they introduced mandatory financial security and precisely regulated its content, thereby, for the first time in the history of maritime labour regulation, addressing the position of abandoned seafarers and their financial claims through binding international rules. The 2016 amendments then extended protection to the working environment by expressly placing harassment and bullying on board within the occupational safety and health framework, coupled with Guideline updates pointing to standards of conduct and the need to consider such phenomena in investigations. The 2018 amendments ensured continuity of

fundamental labour rights during captivity caused by piracy or armed robbery, so that the employment agreement and the payment of wages do not cease due to the expiry of the agreed term or formal acts that the seafarer is objectively unable to control. The 2022 amendments were aimed at strengthening the preconditions for the practical effectiveness of protection in exceptional circumstances. This was achieved through additions relating to repatriation and access to urgent shore-based medical care, alongside strengthened standards concerning communications, social connectivity and basic living conditions on board. Finally, the 2025 amendments continued this direction by clarifying repatriation costs (including medical treatment until the seafarer is fit to travel), introducing a new shore leave regime, recommending the designation of seafarers as key workers to facilitate movement in connection with employment, and strengthening protection against violence and harassment as well as procedural safeguards in complaints procedures (confidentiality, protection against victimisation, and protection of persons involved).

For further improvement of seafarers' labour-law status, this paper proposes three de lege ferenda solutions that should be considered in future amendments to the MLC. First, the issue of a minimum seafarers' wage should be regulated with greater precision, or at least a clearer reference standard should be established, in order to mitigate the effects of unfair competition and to preserve, in the long term, the level of competence required for the safe conduct of shipboard operations. Second, the minimum annual leave entitlement should be more clearly defined and a discussion should be opened on reducing the maximum duration of seafarers' employment agreements from 12 to 6 months, bearing in mind the cumulative effects of fatigue, isolation and mental strain on safety and work quality. Finally, consideration should be given to explicit recognition of seafarers' right to strike, or at least functionally comparable forms of collective action, while taking into account the specificities of maritime service and the potential consequences of disruptions for the safety of navigation and the continuity of global trade.

In conclusion, the regular amendments to the MLC further strengthen seafarers' labour rights and, in substance, bring them close to the treatment enjoyed by shore-based employees. While no convention—including the MLC—is perfect, the possibility of amending the Code through a simplified procedure is therefore particularly important, as it allows the document to be regularly updated and adapted to current developments in shipping and the maritime industry.

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Addressing cultural discount in maritime English communication: An AI-enhanced pedagogical framework

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Abstract: This study addresses the critical challenge of cultural discount, the reduction of communicative efficacy due to socio-cognitive mismatches, in the spoken Maritime English of Chinese EFL learners. Through a comparative corpus analysis of learners and proficient international users, it identifies a distinct competence profile characterised by constrained syntactic packaging, insufficient logical explicitness, and imbalanced pragmatic strategies. Key findings reveal learners' significant gaps in phrasal compression and explicit logical marking, coupled with a strategic overuse of hedges and under use of attitude resources. These quantified gaps serve to operationalise the abstract concept of cultural discount, tracing it to L1 transfer and differing rhetorical norms. In response, the study proposes an AI-enhanced pedagogical ecosystem. Comprising learner profiling, adaptive knowledge graphs, immersive simulation, and data-driven feedback loops, this framework aims to transform identified weaknesses into trainable micro-competencies. The work contributes an analytical tool for understanding cross-cultural communicative barriers and provides a scalable blueprint for cultivating precisely the discourse competencies required for safety and operational effectiveness in global maritime operations.

Keywords: maritime English; cultural discount; AI-enhanced pedagogical framework

1. Introduction

Against the backdrop of the global shipping industry's transition towards greener, smarter and safer operations, the International Maritime Organisation (IMO) and the United Nations Sustainable Development Goals (SDGs) have raised the standards for maritime talent development. Today's maritime professionals are expected to be technically competent, safety-conscious, and environmentally responsible global citizens, capable of collaborating seamlessly in multicultural, high-stakes environments. Central to this collaboration is effective Maritime English communication. Maritime English (ME), a sub-variety of English for Specific Purposes (ESP), serves as the lingua franca for ship-to-ship, ship-to-shore, and multinational crew interactions. Proficiency in ME is not merely advantageous but a competency mandated by regulations and essential for safety. Yet for millions of maritime professionals and students who speak English as a foreign language (EFL), reaching the required proficiency, especially in cross-cultural oral communication, remains a serious challenge. The difficulty extends beyond grammatical accuracy or vocabulary size into subtler domains of pragmatics, discourse norms, and socio-cognitive alignment, precisely where cultural discount frequently occurs.

The term *cultural discount*, originally from media economics, describes the diminished appeal of cultural products in foreign markets. This study adapts the concept to refer specifically to the systematic loss of meaning, intent, and mutual understanding in professional communication caused by different cultural scripts, cognitive frames, and discourse conventions. In high-stakes maritime contexts such as emergency coordination, incident reporting, or multinational technical negotiations, even a slight loss of communicative effectiveness due to cultural discount can lead to misunderstandings, procedural non-compliance, or operational errors. This challenge is particularly acute for Chinese maritime EFL learners, who represent a significant part of the global maritime workforce and encounter a wide linguistic-pragmatic gap between Chinese and English, as well as between Eastern and Western professional discourse norms.

While current Maritime English pedagogy often emphasises terminology and standardised phrases, such as the Standard Marine Communication Phrases (SMCP), it has often neglected to adequately prepare learners for the unstructured, argumentative, and value-negotiating discourses required in intercultural communication and innovative scenarios. Therefore, this study aims to: (1) identify and analyse, through empirical investigation, the specific linguistic and pragmatic features underpinning cultural discount in the oral production of Chinese

maritime EFL learners within simulated professional settings; and (2) propose a measurable metric for assessing competence development. By drawing on data from authentic performance tasks, this study strives to ensure that its findings and implications are relevant to the real-world communicative demands facing future maritime professionals.

2. Literature review

2.1 Cultural discount in maritime English communication

Effective communication is critical for safety in the multicultural shipping industry. While the IMO has mandated English and standardised protocols like SMCP since 1988, a lingua franca by itself proves inadequate. Communication failures remain an accident factor, representing up to 37.77% of incident causation in some studies (Yin et al., 2025) and evident in incidents like the 2021 Ever Given grounding. The efficiency of communication relies on both individual language proficiency and the capacity to apply standard procedures under high-pressure conditions. Therefore, maritime English pedagogy is shifting from survival English to working English, incorporating cognitive academic language proficiency needed for problem-solving and leadership, aligning with the STCW's competency-based approach (Trenkner and Cole, 2012).

Cultural discount occurs when a speaker's intended meaning is misunderstood due to mismatched cognitive frames of reference. Byram's (1997) Intercultural Communicative Competence (ICC) model provides a framework for mitigating this risk, integrating linguistic, sociolinguistic, discourse, and intercultural competencies. Deficits in these areas introduce ambiguities that compromise safety. The mechanism is linked to linguistic relativity and L1 pragmatic transfer, where learners unconsciously apply mother-tongue patterns, leading to pragmatic failure, especially between culturally distant speakers (Kecskes, 2014). Recent work by Zhu (2025) identifies key drivers of this discount across four dimensions: the communicator, the channel, audience reception, and linguistic barriers. It offers a theoretical basis for the quantitative measures employed in the study.

Cross-cultural and contrastive rhetoric research further clarifies this dynamic. Professional genres, such as incident reporting and bridge-team exchanges, require a "speaker-responsible" style characterised by explicit logical connectors, propositional anchoring, and unambiguous illocutionary framing (Connor, 1996). This requirement often conflicts with rhetorical traditions that place greater weight on contextual inference and relational harmony — patterns sometimes described as "listener-responsible". Despite the multicultural composition of modern ship crews, systematic ICC training remains inadequately integrated into standard curricula, even though its alignment with technical language skills is vital for operational safety (Barus et al., 2024; Haryani et al., 2023; Pauksztat, 2021). Accordingly, this study operationalises "discount" as measurable reductions in phrasal density, logical explicitness, and stance-marking accuracy (see section 4.2). The approach also reflects how pragmatic failure and ELF misalignment are modelled in the SLA/pragmatics literature (Björkman, 2014).

2.2 Challenges for Chinese maritime English learners

Chinese learners face distinct challenges: over-reliance on memorised phrases, difficulties with spontaneous discourse management, and limited sociolinguistic awareness (Li and Xi, 2024). Prioritising vocabulary often fails to translate into the ability to construct pragmatically appropriate, complex sentences for real-world tasks (Fan et al., 2018). Deeper rhetorical patterns exacerbate the cultural discount. An internalised "listener-responsible", indirect, and harmony-oriented discourse style may conflict with the direct, explicit, "speaker-responsible" linearity preferred in international maritime workplaces (Connor, 1996). This clash, if unaddressed, hinders effective cross-cultural teamwork.

Instructional traditions emphasising written exams and passive knowledge reception, rather than authentic scenario-based oral practice in Chinese classrooms, widen the gap between test scores and professional application competence (Shi and Fan, 2021). While technology use in teaching is growing, the application of AI and natural language processing to develop tailored solutions targeting maritime-specific discourse and pragmatics to mitigate cross-cultural barriers remains under-explored. This study aims to contribute quantitative insights into the relationship between onboard linguistic and cultural diversity and patterns of communication errors, underscoring the need for targeted ICC training.

3. Research questions

Building on the existing challenges within the Chinese instructional context, this study is guided by the following research questions:

(1) What are the linguistic and pragmatic manifestations of cultural discount in the spontaneous Maritime English production of Chinese EFL learners?

(2) How can AI-enhanced assessment be operationalised to identify and mitigate the impact of culture discount?

4. Methods and procedures

4.1 Empirical material

To analyse the intercultural oral performance of Chinese maritime English learners, the present study compiled a purpose-built corpus using data from the youth competency competition held at the local universities. The data were collected with the informed consent of the organiser. This empirical study examines authentic, multi-modal discourse data, including group discussions and thematic presentations. The data are centred on pressing maritime issues such as safety incident reporting, ship energy efficiency management, marine pollution prevention, and the interpretation of international maritime conventions. The final Chinese Maritime English Learner Corpus (henceforth, CMEL corpus) comprises 20 transcripts totaling 52,750 tokens.

To better contextualise learner performance against international maritime communication standards, a baseline corpus was compiled. This corpus comprises authentic maritime English usage drawn from international forums, including the 2019 United Nations Convention on the Law of the Sea, the 2021 IMO Symposium on Alternative Low-Carbon and Zero-Carbon Fuels, and the 2024 Global Ocean Centre Cities Forum & World Top Scientists Ocean Forum. Following a rigorous selection and validation process, the final International Maritime English (IME) corpus consists of 20 transcribed speech events (51,352 tokens). These corpora comprise discourse from expert speakers from Spain, France, Sweden, Italy, Greece, and Croatia.

All recordings were orthographically transcribed following a hybrid set of principles adapted for L2 learner spontaneous speech. The core conventions were derived from the Louvain International Database of Spoken English Interlanguage (LINDSEI) guidelines (Gilquin, De Cock, and Granger, 2010), which are specifically designed to capture the features of learner language. To account for the maritime-specific register and situational context, these were supplemented by selective annotation schemes used in maritime communication research (e.g., for standard maritime communication phrases and operational scenarios). The data were further refined to ensure representativeness by controlling for text type (oral production transcriptions) and language background (IME vs. CMEL). All comparative measures are normalised using relative frequency per 1,000 words. Further details of the datasets are summarised in Table 1.

Table 1. Description of the corpora

Group	Tokens	av. Tokens talk	Number of the talks collected
CMEL	52,750	2,635	20
IME	51,352	2,567	20

4.2 Operationalisation of analytical dimensions

Guided by the International Maritime English Conferences (IMECs) and established maritime discourse research (e.g., John et al., 2019; Schriever, 2009), this study adopts a fine-grained analytical scheme to assess the oral performance of Chinese maritime English learners and identify markers indicative of cultural discount. The operationalisation of each dimension, detailed below, incorporates established methods from corpus linguistics, discourse analysis, and intercultural pragmatics to ensure reliability.

(1) Syntactic sophistication: Following Halliday's (1989) assertion that the complexity of spoken language is fundamentally realised through grammatical intricacy, this dimension focuses on the phrasal density of learner output. Specifically, it is operationalised through two key indices measured per Analysis of Speech unit (AS-unit): the number of complex nominals per AS-unit (CN/AS) and the number of Verb Phrases per AS-unit (VP/AS). Complex nominals are defined as noun phrases containing modifiers beyond a determiner and a head noun (e.g., adjectives, prepositional phrases, relative clauses), following the operationalisation in L2 syntactic complexity research (Lu, 2011). Given the vital role of AS-units as a reliable measure for spoken discourse, defined as an independent clause with its subordinate clauses (Foster, Tonkyn and Wigglesworth, 2000), and

considering the inherent difficulty in their automated segmentation due to pragmatic and functional boundaries, the coding was performed using computer-assisted techniques followed by manual double-checking.

(2) Semantic clarity: This dimension assesses the precision, explicitness, and coherence of propositional meaning, qualities critical for preventing ambiguity in high-stakes maritime operations where miscommunication can have severe consequences. The appropriate use of logical connectives (e.g., *however, furthermore*) is quantified in this study. This metric evaluates the speaker's ability to explicitly signal causal, contrastive, and elaborative relationships between ideas, a key component of informational coherence in professional discourse (McCarthy and Carter, 2014).

(3) Use of discourse strategies: Moving beyond purely formal linguistic features, this dimension examines socio-pragmatic and attitudinal alignment with IME norms. It directly operationalises the detection of cultural discount, the systematic erosion of communicative efficacy arising from different cultural scripts and cognitive frames (Kecskes, 2014). Analysis focuses on the presence, absence, or atypical use of hedging markers (HE) (e.g., *perhaps, might*) and attitude cues (AT) (e.g., *unfortunately, hopefully*). Their use is evaluated against established conventions in IME. A lack of these resources, or their use in ways rooted in high-context, relationally-oriented Chinese norms within the low-context, task-oriented maritime setting, signals a cultural discount effect (Hyland, 2005). This effect may lead others to perceive the speaker as abrupt, tentative, or emotionally inappropriate.

By integrating these dimensions, the analytical framework generates a nuanced profile of a learner's cross-cultural oral proficiency. It moves past superficial error counts to detect not only where linguistic or pragmatic weaknesses occur but also why they arise, often tracing them to specific socio-cognitive origins that manifest as cultural discount. This detailed analysis provides the empirical basis for designing targeted, evidence-based pedagogical interventions within the proposed Language-Scenario-Culture framework.

To ensure coding reliability, the inter-rater agreement was assessed using Cohen's Kappa, a statistical measure for evaluating consistency between annotators in an identification task. Two trained raters independently segmented all transcripts into AS-units and identified the target linguistic features. Any disagreements were resolved through discussion. The results indicated a high level of agreement across all coded categories: κ (CN/AS) = .812, $p < .001$; κ (VP/AS) = .789, $p < .001$; κ (LC) = .800, $p = .00$; κ (HE) = .759, $p < .000$; κ (AT) = .778, $p = .00$.

5. Results and discussion

5.1 Empirical overview of group performance

A descriptive overview of the performance metrics for both speaker groups is presented in Table 2. The data reveal notable differences in the central tendencies of the measured variables between Chinese Maritime English Learners (CMEL) and the International Maritime English (IME) users.

Table 2. Descriptive statistics for key performance indicators

Dimension	Indicator	CMEL		IME	
		M	SD	M	SD
Syntactic sophistication	CN/AS	1.82	0.41	2.43	0.34
	VP/AS	1.05	0.19	0.81	0.16
Semantic clarity	LC	4.42	1.55	6.27	1.38
Use of discourse strategies	HE	2.05	1.58	1.22	1.09
	AT	6.31	2.89	8.45	2.56

Note: M = Mean; SD = Standard Deviation.

To determine the statistical significance of the observed differences between the CMEL and IME groups, independent-samples t-tests were conducted for data meeting assumptions of normality and homogeneity of variances; otherwise, Mann-Whitney U tests were employed. Effect sizes (Cohen's d or r) were calculated to measure the size of the differences. The results of these inferential analyses are summarised in Table 3.

Table 3. Results of inferential statistical analyses

Dimension	Indicator	Test	Statistic	P value	Cohen's d/r	Significance & Effect
Syntactic sophistication	CN/AS	Independent t-test	t(40)=-4.21	<0.001***	1.34	IME > CMEL (large)
	VP/AS	Mann-Whitney U	U=178.5	0.412	0.25	n.s. (small)
Semantic clarity	Logical connectives (per 1,000)	Independent t-test	t(40) = -4.89	<0.001***	1.48	IME > CMEL (large)
Use of discourse strategies	Hedging markers (per 1,000)	Independent t-test	t(40) = -6.72	<0.001**	2.14	IME ＜CMEL (large)
	Attitude cues (per 1,000)	Mann-Whitney U	U = 105.0	0.001	0.55	IME > CMEL (large)

Note: n.s. stands for "not significant". Effect size guidelines: d: small(≈0.2), medium(≈0.5), large(≈0.8); r: small (≈0.10), medium (≈0.30), large (≈0.50), and very large (≈0.70) (Cohen's, 2013).

Comparative analysis reveals differences in syntax, semantic, and pragmatic levels between CMEL learners and the IME standard. These patterns provide empirical evidence that cultural discount, a loss of communicative efficiency due to socio-cognitive mismatches, is a multi-layered phenomenon in professional second language maritime discourse.

5.2 Syntactic difference and inefficient information packaging

At the syntactic level, a clear difference was found in phrasal density. IME users produced more complex noun phrases per AS-unit (CN/AS) than CMEL learners did ($t = -4.21$, $p < 0.001$, $d = 1.34$). By contrast, there was no meaningful difference in verb phrase density (VP/AS) between the two groups ($U = 178.5$, $p = 0.412$, $r = .25$). This selective gap points to a specific weakness: compressing information into noun phrases, a key skill for efficient information packaging in English.

IME users employ right-branching post-modification (e.g., prepositional phrases, relative clauses) to achieve high informational density within a single clausal unit, a strategy aligned with the demands of precise technical communication (Biber et al., 2011). Learners, however, can handle basic clause structures, but they struggle with the demanding job of packing information into dense noun phrases. It often requires a right-branching structure, wherein modifying elements follow the head noun. Two theoretical views help explain this pattern. First, Skehan's (1998) Trade-off Hypothesis suggests that limited working memory forces learners to choose between complexity, accuracy, and fluency. Thus, they may prioritise fluency and structural accuracy at the expense of syntactic complexity (i.e., dense noun phrases). Second, L1 transfer plays a role. Unlike English, which places modifiers after the head noun (right-branching), Mandarin Chinese is a head-final language that strongly prefers pre-modification (left-branching), giving it a very different blueprint for building noun phrases (Li and Thompson, 1981). This L1 habit might disrupt the online processing required for English-style right-branching structures (Gass and Schachter, 1989), leading to cultural discount manifested as a loss of informational efficiency and reduced nativelikeness in packaging (Jarvis and Pavlenko, 2008).

5.3 Semantic difference and insufficient logical explicitness

Regarding semantic clarity, IME users employed logical connectors at a significantly higher frequency (large effect) than CMEL learners did ($t = -4.89$, $p < 0.001$, $d = 1.48$). This means they marked causal, contrastive and additive relationships between ideas in a more explicit and systematic way. CMEL learners, by contrast, do not use these logical signs as explicitly. It suggests they rely less on a "speaker-responsible" rhetoric. In high-consequence maritime operations, clear communication is vital. Explicit logical marking reduces listeners' cognitive load and prevents misinterpretation of procedures, causes, and arguments. When listeners lack this explicitness, the discourse becomes less transparent and place a heavier burden on the listener, a real risk in safety-critical maritime settings.

The under-use of logical connectors may be linked to different rhetorical traditions. English professional discourse typically follows a "speaker-responsible" convention, where the speaker takes the main responsibility for being clear and for using explicit signals (Hinds, 1987). In contrast, some analyses of Chinese rhetoric point to a greater tendency towards "listener-responsibility". This style relies more on shared context, inferred

relationships, and a holistic understanding (Connor, 1996; Scollon and Scollon, 2001). CMEL learners, possibly influenced by this L1 rhetorical preference. As a result, they may not fully compensate for the lack of shared context in international, low-context maritime settings. Their failure to adopt a more explicit, linear and connector-rich style creates a cultural discount, at the level of discourse coherence and logical transparency. This can put mutual understanding at risk.

5.4 Discourse strategies and sociopragmatic misalignment

Discourse analysis reveals a strategic imbalance in CMEL learners' pragmatic choices. CMEL learners over-relied on hedges ($t(40) = -6.72$, $p < 0.001$, $d = 2.14$) yet significantly under-used attitudinal resources compared to IME speakers ($U = 105.0$, $p = 0.001$, $r = .55$). This difference is not a contradiction, instead, it reveals a nuanced mismatch in pragmatic choice. The overuse of hedges likely reflects a transfer from Chinese interactional norms, where indirectness and mitigated assertions are valued for maintaining group harmony and saving face (Gu, 1990). However, in the low-context, task-focused maritime workplace, this tentativeness can be misread as a lack of confidence or an evasion of responsibility. On the other hand, under-using attitude markers limits learners' ability to construct an engaged, evaluative professional persona and to build interpersonal rapport with interlocutors (Hyland, 2005). These two imbalances, over-hedging and under-engagement, point to an underdeveloped pragmatic competence. It is not merely a linguistic shortfall but a sociopragmatic cultural discount, wherein a grammatically sound communicative style fails to achieve the intended persuasive impact and interpersonal alignment expected by the target discourse community. The gap likely stems from both inadequate pedagogical focus on the strategic use of metadiscourse in maritime English and negative pragmatic transfer from L1 interactional norms.

Overall, the findings underscore that professional maritime communication requires more than grammatical accuracy; it demands control of discourse-level norms in information packaging, logical exposition, and stance-taking. Instructional practice should therefore extend beyond sentence-level instruction to include explicit training in discourse organisation and cross-cultural rhetorical awareness.

6. Towards an AI-enhanced MICC pedagogical ecosystem

To address the identified cultural discount, this study proposes the Maritime Intercultural Communicative Competence (MICC) Enhancement Ecosystem. Grounded in sociocultural and situated learning theories, this framework moves beyond traditional classroom instruction by embedding learning within simulated professional communities. It comprises four integrated stages (see Figure 1).

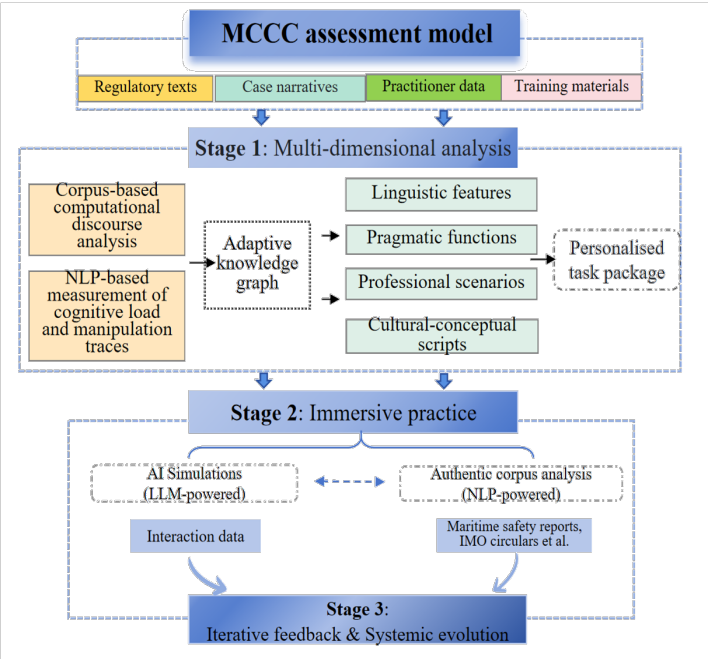


Figure 1. AI-enhanced MICC pedagogical ecosystem

Stage 1: Diagnostic profiling. The system analyses learners' oral production to calculate key linguistic indices and assesses cultural-cognitive traits through scenario-based tasks. This yields a dynamic learner profile that visualises gaps against expert benchmarks and predicts context-specific risks of cultural discount.

Stage 2: Adaptive knowledge graph and personalised pathway. At the core is a knowledge graph linking linguistic forms to professional scenarios with four node types: linguistic features, pragmatic functions, professional scenarios, and cultural-conceptual scripts. Activated by the learner profile, it performs a gap analysis and assembles personalised learning packages. For instance, a deficit in noun phrase density triggers a "Noun Phrase Expansion" module, transforming simple clauses into compact, professional utterances. Similarly, a lack of logical connectives prompts a "Discourse Cohesion" package, using contrastive analysis of expert texts and gap-filling tasks. Pragmatic imbalances lead to a "Stance-Taking" module involving analysis of transcribed interactions and structured role-plays to practice hedging and attitude usage.

Stage 3: Immersive, grounded practice. This experiential stage combines two approaches. First, AI-powered simulations place learners in high-fidelity, interactive scenarios (e.g., PSC inspections, multinational meetings), with agents programmed to react according to cross-cultural behavioral norms. Second, authentic corpus analysis tasks employ NLP tools to let learners deconstruct real-world texts (e.g., IMO circulars, investigation reports), highlighting how professional values like safety and compliance are encoded in language. This enables learners to deconstruct the cultural logic and epistemic norms of the international maritime discourse community, moving from passive reading to active, critical engagement with industry discourse.

Stage 4: Iterative feedback and systemic evolution. A dual-layer feedback mechanism supports growth. Real-time feedback allows for immediate correction. Post-task, a comprehensive debrief provides a multidimensional analysis against expert models. All interaction data feed back into the system, refining scenarios and optimising learning pathways. It creates a self-improving ecosystem that adapts to both learner needs and the evolving demands of the maritime profession.

7. Conclusion

This study identifies a clear profile of Chinese maritime English learners, marked by underdeveloped syntactic complexity, logical explicitness, and pragmatic strategy use. The identified gaps, specifically in low noun phrase density, logical connector usage, and the imbalanced use of hedging versus attitude resources, illustrate how cultural discount operates in professional L2 spoken discourse. The findings underscore that effective maritime communication in international settings demands more than lexical and grammatical accuracy; it requires mastery of discourse-level packaging, explicit logical scaffolding, and interpersonal negotiation suited to a high-stakes, low-context environment. To close the gaps, pedagogy must move beyond sentence-level instruction. Scenario-based training should raise learners' awareness of how linguistic forms function within specific professional contexts. Building on this, the study proposes an AI-enhanced, theory-grounded pedagogical ecosystem. This framework translates abstract cultural discount phenomena into trainable micro-competencies, integrating adaptive knowledge graphs with immersive simulation, and data-driven feedback within a closed-loop learning system. The primary contribution is twofold: theoretically, it operationalises cultural discount within the maritime L2 context; practically, it provides a scalable blueprint for developing precise, culturally-aware communicative competence. Future work will involve prototype development and empirical validation of the proposed system and its assessment indices.

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A comparative study on the use of VR and actual machinery in teaching centrifugal pump operations to marine engineering students

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Abstract: This study employed a quasi-experimental comparative design to evaluate the effectiveness of Virtual Reality (VR) versus actual machinery in training marine engineering students on centrifugal pump operation. Using a mixed method approach, 39 Indian students with Mechanical Engineering background were divided into VR and actual machinery groups. Quantitative data were collected through standardized written multiple-choice and oral assessments administered by an external assessor, as well as Likert-scale feedback forms. Qualitative data were gathered through evaluation forms and focus group discussions. Findings revealed that VR training was nearly as effective as actual machinery in conveying technical knowledge. VR participants reported higher satisfaction, clearer conceptual understanding, and appreciated the safe, consequence-free environment that supported procedural sequence learning and repeated practice. However, VR lacked tactile realism and occasionally encouraged passive learning due to reliance on visual prompts. In contrast, training in actual machinery was crucial for developing sensory-motor skills and component familiarity but limited by safety-risks, restricted access, and reduced opportunities for repetition. The study concludes that VR and actual machinery provide complementary learning experiences and should not be used independently. A sequential blended approach combining theory, and practices in VR then in actual machinery is strongly recommended for Maritime Education and Training.

Keywords: Virtual reality; Maritime Education and Training (MET), comparative study

1. Introduction

Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) has emerged as a vital educational tool that offers an authentic learning experience. The growing interest in the adoption of this technological innovation in education lies in its potential to enrich learning experiences and improve retention and understanding of concepts through immersive learning environments, interactive simulations, and collaborative activities (Al-Harthy, Balushi and Badi, 2023; Fernández-Cerero, Fernández-Batanero and Montenegro-Rueda, 2025). Moreover, Burke, Crompton, and Nickel (2025) identified four ways in which XR facilitates learning: simulation, gaming, visualization, and problem-solving.

Several studies have shown the positive effects of XR in enabling learning. Zolezzi et al. (2024) found that XR technologies, combined with gamification, enhanced student engagement, comprehension, and exam readiness. In English as Foreign Language (EFL) education, immersive VR learning, combined with a virtual classroom map, improved writing performance, sustained student interest, reduced fear of failure, and strengthened a culture of sharing (Huang and Macgilchrist, 2024). In the area of Science, Technology, Engineering, Arts, and Mathematics (STEAM) education, Zhan et al. (2024) proved that VR-enhanced teaching aids (VETAs) fostered more interactive and student-centered classrooms, while Jiang et al. (2024) found mixed results in their study: the students got interested in XR tools, but the said tools did not necessarily increase their

interest in the program, so the study maintained that the interactions in the classroom had more impact on the motivation of the students than the use of technology.

In maritime education and training (MET), the following contributions of XR have also been noted: knowledge improvement, retention or acquisition (Miyusov, Nikolaieva, and Smolets, 2022; Vakil, 2023; Sadiku, Asekunte, and Sadiku, 2025; Tusher et al., 2026); safe learning avenue for skills development (Aylward et al., 2021; Christopoulos and Stylios, 2024); and teamwork and situational awareness enhancement (D' Augusta et al., 2024) among other aspects.

Despite the gains from using XR in education, some challenges have also been identified. These challenges include pedagogy, sustainability and adaptability (Abeywardena, 2023); ease of use, including health issues, and acquisition and maintenance cost (Sadiku, Asekunte, and Sadiku, 2025; Vakil, 2023); professional qualifications, learner factors, and technological accessibility and capabilities (Obeidallah, Ahmad, and Qutishat, 2023); and regulatory guidelines (Tusher et al., 2026; Sadiku, Asekunte, and Sadiku, 2025).

Existing studies have explored various applications and limitations of XR in education broadly, and in MET more specifically. Within MET, research has concentrated on navigation (D' Augusta et al., 2024; Miyusov, Nikolaieva and Smolets, 2022; Aylward et al., 2021), firefighting (Kazura, Suhrab and Noor, 2024), and general applications of XR (Vakil, 2023). Complementary works include Christopoulos and Stylios's (2024) review of XR in navigation, Sadiku, Asekunte and Sadiku's (2025) conceptual paper on immersive technologies in the maritime industry, and Tusher et al.'s (2026) study of perceptions among students and professionals, which notably did not assess actual XR use. Despite this growing body of scholarship, the literature remains disproportionately focused on navigational training and conceptual discussions, with limited empirical attention to the engineering domain. In particular, there is a lack of studies examining how XR can be applied to the practical development of engineering competencies among maritime students, leaving a critical gap in understanding its role in enhancing technical skill acquisition.

Anchored on constructivism, this study aimed to compare the effectiveness of VR and physical equipment in facilitating the learning of marine engineering students in centrifugal pump operation. Constructivism posits that students actively construct knowledge as opposed to being passive 'blank slates' (Narayan et al., 2013). Applied to the present study, the student-participants experienced dismantling a centrifugal pump using the actual machinery and the VR assistance. After the experience, they were asked to reflect and evaluate the effect of the activity to their learning.

2. Methodology

This study used a quasi-experimental, comparative research design to evaluate the effectiveness of VR vs actual machinery, specifically in the delivery of centrifugal pump operation. The use of a comparative framework allowed the researchers to isolate the delivery modality as the primary independent variable, considering also other variables such as student assessment scores and satisfaction.

The research employed a mixed-method approach, integrating both quantitative and qualitative data collection. The quantitative methods included both standardized written and oral assessments to measure the students' cognitive retention and ability to articulate technical procedures. The assessment scores were supplemented by structured feedback and evaluation from the Likert-scale and open-ended questions survey. The qualitative component was based on data from focus groups interviews. The triangulation of the different sets of data served to increase the validity of research findings and ensured the integration of sound statistics and contextual detail required in order to help in the instructional design and VR integration of future exercises.

The research included 39 marine engineering students who were grouped into four: Groups 1 and 2, composed of 10 students each, used VR, and Groups 3 and 4 with 10 students and 9 students respectively, used the actual centrifugal pump. Instructors led the training exercises on the operation of the centrifugal pump for all groups. After the exercises were conducted, an external assessor from another METI administered the oral assessment. To avoid biases, the assessor was not told which modality the students used. Also, a written multiple-choice questionnaire was given to the students.

The quantitative and qualitative data were analyzed independently before being triangulated to draw comprehensive conclusions. Two groups with mixed participants from VR and physical groups formed the focus groups A and B. Thematic analysis yielded four main themes: Perceived learning effectiveness of VR vs

actual machinery training; safety, risk, and error in simulation; role of instructor; and VR training design and usability.

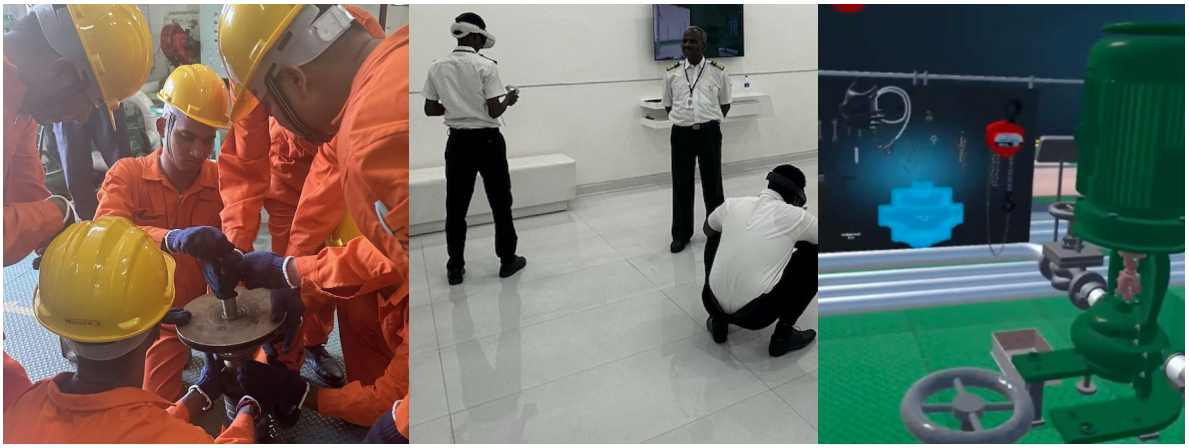


Figure 1. Student participants dismantling a centrifugal pump using actual machinery (left) and VR (center and right).

3. Findings

3.1 Quantitative data

The assessment scores, comprising both oral and multiple-choice questions (MCQ), indicate that students achieved comparable learning outcomes regardless of the medium used. In terms of mean percentage, Table 1 shows that there is a marginal difference of only 1.25% between the two groups. This suggests that VR is nearly as effective as physical equipment in conveying the technical knowledge required for centrifugal pump operation and maintenance. Table 2 presents the mean scores based on the perception of the participants through the evaluation and feedback form.

Table 1. Summary of assessment scores.

Group (users)	Sample size (n)	Mean Score (Oral + MCQ) (out of 40)	Mean Percentage (%)
VR	20	23.50	58.75%
Actual machinery	19	24.00	60.00%

Table 2. Evaluation and feedback of students.

Evaluation Criteria	VR Mean	Interpretation	Actual machinery Mean	Interpretation
Clear learning outcomes	4.53	Very Effective	4.43	Effective
Understanding of centrifugal pump principles/operation	4.53	Very Effective	4.33	Effective
Assessment tasks reflected knowledge and skills taught	4.42	Effective	4.38	Effective

Realistic/relevant environment	4.26	Effective	4.29	Effective
Clear and helpful instructor's guidance and support	4.26	Effective	4.29	Effective
Overall (satisfaction) assessment	4.53	Very Effective	4.29	Effective

In terms of conceptual clarity, participants using VR demonstrated a stronger understanding of the principles and operation of the centrifugal pump (4.53) than those using the actual machinery (4.33). VR users also perceived the learning outcomes to be clearer (4.53) compared with the actual machinery group (4.43). In addition, assessment tasks in the VR group were rated slightly higher in reflecting the knowledge and skills taught (4.42) than in the actual machinery group (4.29). Overall, the VR group reported greater satisfaction (4.53) than the actual machinery group (4.29). On the other hand, the actual machinery group perceived the training environment as marginally more realistic (4.29) than the VR group (4.26). They also reported receiving slightly clearer and more helpful instructor guidance and support (4.29) compared with the VR group (4.26).

3.2 Qualitative data

The qualitative findings were drawn from the evaluation and feedback forms as well as the focus group discussions with the participants. The comments provided by participants highlight specific strengths and weaknesses of each modality.

3.2.1 Evaluation and feedback

Regarding VR equipment, students highlighted its effectiveness for visualization and the helpful step-by-step guidance provided by the program. Moreover, the VR environment offered a safe 1:1 experience that allowed participants to gain essential experience before handling the actual machinery. On the other hand, students reported technical concerns, including glitches during the task performance and a lack of detail regarding tool specifications, such as spanner sizes. Ergonomic discomfort was another notable concern, wherein one student reported experiencing dizziness after using the VR equipment continuously for 40 minutes.

For the actual machinery, the primary strengths identified were the direct exposure to machinery itself and the opportunity to use actual tools. The training also successfully fostered teamwork among the students. However, this modality faced limitations, such as batch sizes that participants suggested should be reduced to improve learning experience. Furthermore, students indicated a need for more repetitive practice at least twice with changing roles to better build their confidence in operating the equipment.

The participants repeatedly emphasized the integration of both training methods rather than choosing one over the other. Here, VR is used as an initial training phase to enable students to practice procedures and reduce errors before working with physical equipment. To further improve the experience, students suggested enhancing VR features by adding an instructor within the virtual environment and introducing specific training difficulty levels, such as "easy, average, and difficult."

3.2.2 Focus group

Four themes emerged in the analysis: Perceived learning effectiveness of VR vs actual machinery training; safety, risk, and error in simulation; role of instructor; and VR training design and usability.

3.2.2.1 Perceived learning effectiveness of VR vs Physical training

Participants reflected on how effective the training using VR and actual machinery helped them understand and retain knowledge about the procedures for operating the centrifugal pump, comparing the strengths and weaknesses of each modality. VR demonstrated significant strengths in procedural sequence learning but showed clear limitations for physical component identification. The consensus by both groups on the role of VR in procedural learning established that VR was particularly effective for teaching operational sequences and contextual procedural knowledge while falling short in supporting the component recognition required for its

practical application. As for the actual machinery training, it created a connection between the brain and the muscle sensations thereby strengthening psychomotor skill development. The participants from both groups stressed the importance of this coordination between mind and body in their learning. Physical sensations, such as weight, vibration, and tactile resistance, provided immediate operational feedback, which enabled the proper application of the technique in a way that VR cannot replicate.

Both VR and actual machinery training created distinct cognitive profiles that significantly impacted learning outcomes and retention capabilities. Physical training created heightened mental engagement driven by safety awareness, while VR training demonstrated unique advantages for spatial memory formation. However, both groups also revealed that current VR systems often created passive learners who focused on the location of the object and visual prompts rather than developing independent procedural understanding. This consistent finding across both focus groups demonstrates how both modalities presented strengths and limitations in cognitive processing that must be carefully balanced to optimize learning effectiveness across different training objectives and learner experience levels.

Moreover, repeated practice in VR provides significant advantages for familiarization but requires strategic design to maximize learning effectiveness and knowledge retention. Both focus groups described that VR enabled valuable preparatory training through structured repetition without physical constraints. The data also consistently revealed that VR enhances spatial and contextual memory retention beyond theoretical instruction. On the other hand, the students noted one limitation of the VR and that is its tendency to focus so much on procedures, overshadowing deeper cognitive processing. As participants from Group A mentioned, they were preoccupied with the steps to be followed rather than understanding the underlying principles of the task. This suggests that in order for VR to be an effective learning tool, it is important to balance its immersive features with a well-designed instruction that does not only result in execution of procedures but also understanding of concepts.

3.2.2.2 Safety, risk, and error in simulation

Participants agreed that VR offers a safe environment to conduct trials and errors of high-risk tasks, make mistakes, and learn from consequences without any physical danger, in contrast to the risks that may be associated with physical training. VR transforms safety from merely preventing harm to actively creating opportunities for deeper learning through failure, enabling trainees to bridge theoretical knowledge with practical application without harmful consequences. Moreover, physical safety hazards (risks associated with heavy equipment components falling and injuries caused by a single-person handling of heavy components) in practical training constitute significant concerns that VR training completely eliminates through environmental separation from hazardous equipment.

On the other hand, the VR training exercise employed overly restrictive error handling that prevented authentic learning through consequence discovery, creating a mismatch between simulated and real-world error patterns. Group A highlighted that VR systems immediately halted progression at the first error rather than allowing mistakes to cascade through subsequent steps as would happen in real life. This approach contradicts the participants' reports of how genuine skill development occurs in physical training environments, where mistakes often become apparent only later in the process. This unique perspective reveals a fundamental disconnect between traditional VR instructional design, which prioritizes error prevention, and the reality of technical work, where understanding the consequences of errors is in itself a fundamental learning experience. Unlike actual machinery training, where trainees must learn to trace problems back to their source through root cause analysis, the current VR exercise design created artificial learning conditions that do not prepare trainees for real-world scenarios in which identifying root causes of problems that manifest much later in a process is essential to becoming a competent marine engineer.

3.2.2.3 Role of instructor

Real-time instructor support emerged as a critical component in both training modalities, particularly for procedural tasks requiring immediate clarification. Participants in both groups felt lost without the presence and guidance of the instructor, revealing their dependency on immediate instructor presence during VR operation. In addition, both focus groups consistently identified the inability to resolve component identification challenges without interrupting sessions to seek external help. Participants expressed that they sought the

instructor's help during procedural tasks in VR, while physical environments allowed trainees to observe peers and receive spontaneous clarification through instructor movement within the workspace, which was an advantage over the current virtual exercise. To address the issue, both groups suggested a virtual instructor integration to ensure immediate feedback and assistance during difficulties.

3.2.2.4 VR exercise design and usability

The participants also identified various technical and instructional limitations in the current VR exercise design and proposed improvements to enhance realism, usability, and educational value. For example, the absence of the physical sense of touch represents a fundamental limitation in the use of VR training that directly compromises technical skill development. Both groups reported struggling to identify components without the sense of touch, which is a fundamental gap between virtual training and the physical demands of technical work, where muscle memory and sensory awareness are essential. The shared experiences of both groups demonstrated that the current VR instruction exercise design failed to balance simplicity with the sufficient detail required for effective skill acquisition across varying user experience levels. Furthermore, equipment usability issues in the VR training exercise disrupted workflow and created a significant cognitive burden for users. Both focus groups consistently reported equipment disappearance during boundary transitions, demonstrating how challenges in navigation in the virtual space consumed valuable learning time. Component identification difficulties and problems with visual-only instructions were other shared challenges. The current multimodal options are insufficient to support diverse learning needs. These convergences of navigation and usability challenges across both focus groups underscore how fundamental design flaws in spatial awareness, object persistence, and instruction delivery actively undermine the learning experience and reduce the efficiency of VR training systems for technical skill development.

3.2.2.5 Overall participants' perception - Blended approach

Participants suggested a learning sequence where they have a lecture with their instructor in the classroom first, then immersion and practice with the VR, then practical exercise with the actual machinery. This sequence helps them clarify concepts, initially practice in a safe environment and boost their confidence. With this sequence, VR serves as a bridge between conceptual understanding and practical execution. VR turns intangible conceptual knowledge into something concrete and lasting. Addressing the participants' concern that the absence of VR and going directly to physical practice may lead them to commit more errors than necessary, VR makes them more prepared and confident to perform the actual exercise. With the proposed sequence, the students build on mastering the procedures first, leading to minimized errors when they operate the actual equipment.

In addition, the student-participants perceive VR and the physical equipment as complementing each other. They both have distinct but interdependent roles to play in the learning of the students. Participants shared that access to the physical equipment is limited and operating it may pose higher risk. With VR, learning a skill and performing the tasks in the laboratory become safe and cost-effective. On the other hand, participants also appreciated the real-world human interaction that the physical equipment offers, which cannot be experienced in the VR. Combined together, VR and physical practice complete what the other lacks while ensuring a deep learning of the students.

4 Discussion

The strengths and weaknesses identified by the students on the use of VR and the physical equipment in the operation of centrifugal pumps reveal the complementary relationship between the two. Each learning modality has its value in making the students learn the required concepts and the skills, while providing what the other modality lacks. As Miyusov, Nikolaieva, and Smolets (2022) suggested, maximum learning results from hybridizing the learning setup, with VR serving as a bridge between theory and practice. In this study, student-interviewees highlighted the value of XR as an essential connection between classroom discussion and actual practice in dismantling the centrifugal pump.

Aside from memory retention (Miyusov, Nikolaieva and Smolets, 2022; Vakil, 2023; Sadiku, Asekunte and Sadiku, 2025; Tusher et al., 2026), VR enables learning from catastrophic errors without physical consequences as it enables visualization (Burke, Crompton and Nickel, 2025) and acquisition of a skill, which

may require repetitions of tasks, in a safe learning environment (Aylward et al., 2021; Christopoulos & Stylios, 2024). The collective evidence positions VR not merely as an alternative teaching tool and piece of equipment, but as an inherently safer approach that converts high-risk learning experiences into safe pedagogical encounters by systematically removing physical danger during competence development.

Notably, VR serves as an excellent preparatory tool that reduces errors during the operation of centrifugal pumps, particularly for beginners, but it cannot replace physical training when precise component identification is essential for safe and effective task execution. Overall, the data illustrate that participants consider physical sensation not merely a supplementary element but rather the essential component of practical skill acquisition, creating authentic neural pathways that seamlessly integrate cognitive processing with sensory experience to build stronger learning capabilities for real-world equipment handling.

The noted issues in using VR in centrifugal pump operation, like glitches and ergonomic concerns, echo the findings of previous researchers (Obeidallah, Ahmad, and Qutishat, 2023; Vakil, 2023; Sadiku, Asekunte, and Sadiku, 2025), showing that the problems encountered by maritime students are not isolated and context-specific, but a common and recurring technological shortcoming. Notwithstanding the identified problems, the findings of this study demonstrate the viability and effectiveness of integrating VR into the teaching and learning of centrifugal operation. However, there is a need for careful planning and design to meet the needs of the students and the specifications of the course.

5 Conclusion, Recommendations, Limitations

This study contributed to the growing literature on the use of XR in education in general, and in MET in particular. Empirical investigations into how students operate and manipulate engine room machinery using XR remain limited; therefore, this study contributes to addressing that gap in the field. Findings demonstrated the potential of XR in enhancing the learning experience of maritime students through its immersive and safety features. However, some challenges call for recalibration to maximize the promises of this technology. While the scope of the study was limited to only one institution and one topic in a course in the marine engineering program, some recommendations are presented. Careful consideration should be paid to the design and programming of the XR tool to ensure that technical issues and physical discomfort are eliminated, and that the content meets the theoretical and practical needs of students. It is also recommended that the blended sequence of the use of XR with the actual training equipment be designed in a thorough and optimal manner to ensure maximum learning gains. As for future studies, researchers may focus on the feasibility of XR in other topics or courses within the same or at other institutions for comparison purposes. They may also modify the design of the exercise to blend VR and actual machinery in the operation of centrifugal pumps, or other operations, and then test its effectiveness.

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Effectiveness and efficiency of co-operation between IAMU member universities: A SWOT analysis

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Abstract: In today's dynamic world, collaboration and co-operation between universities are essential towards sharing resources and capabilities to deal with accelerating innovation and complex global challenges. In the same spirit, the Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T) of co-operation between two IAMU member universities, *i.e.*, Satakunta University of Applied Sciences (SAMK) and the Australian Maritime College (AMC), in relation to economic, social, and environmental viability were studied. The methods used were a literature review, workshops between SAMK and AMC, and individual expert work. The results revealed various (internal) strengths and threats of SAMK co-operation, as well as (external) opportunities and threats that exist. Social aspects were the most common among all SWOT categories. The aim of this research study was to develop practical guidelines on international co-operation for IAMU.

Keywords: co-operation; collaboration; maritime; SWOT; universities

1. Introduction

The maritime domain is an international industry undergoing changes, such as the green transition, digitalization, and human elements (Khabir et al., 2025). Sustainable global collaboration in the development and implementation of maritime education and training (MET) of the workforce is essential within these changes. To maintain the sustainability of international shipping, there is a need for the effectiveness and efficiency of maritime workforce education and training.

This scheme has already been established via IAMU, the International Association of Maritime Universities. IAMU's primary goal is to convene MET institutions to establish a global forum for maritime education and research. To do that, IAMU funds and supports various projects, develops several working groups on significant issues, and hosts annual events such as academic conferences. Over the years, the IAMU-supported co-operation has fostered one-to-one collaboration among IAMU member universities (IAMU, n.d.-a). This shows that IAMU's actions and policies have many facets that go beyond its defined scope and are greatly affecting the member universities involved. Although essential, the causal effects of IAMU's efforts and their consequences for developing its members' collaborations have not yet been evaluated.

The scope of our study is comprehensive, encompassing IAMU-supported activities through to one-to-one co-operation between member universities. The study aimed to combine SWOT (i.e., Strengths & Weaknesses and Opportunities & Threats) with selected sustainability factors. The S and W are scrutinizing internal aspects of the organization, and the O and T are assessing the external ones, respectively (Bamford et al., 2024, p. 42). Sustainability has various definitions, and in this study, the Triple Bottom Line (TBL) was used, a sustainability framework that measures business performance based on economic growth while balancing social equity and environmental responsibility (Elkington, 1997a).

2. Materials and methods

To better understand IAMU policy and actions regarding these collaborations, we conducted a study on the effectiveness and efficiency of cooperation between two IAMU universities, *i.e.*, Satakunta University of Applied Sciences (SAMK) and the Australian Maritime College (AMC). These universities were selected for

the case study, as they have done intensive co-operation over the years. joint IAMU projects, conference papers, and other activities (Keinänen-Toivola et al., 2025). In our study, we utilized the SWOT (Strengths, Weaknesses, Opportunities, and Threats) framework for organizational analysis within its operational environment and to develop practical guidance for IAMU member universities on international co-operation.

The methods used were a literature review, three online workshops between SAMK & AMC on 20th and 25th of November, and 1st of December 2025, and one face-to-face workshop on 23rd of February 2026, as well as individual work by the experts. The results from the workshops were collected in tables, consisting of each dimension of SWOT (Strengths, Weaknesses, Opportunities, or Threats), which aspect of sustainability (environmental, social, economic) the findings present, what the dimension means (explanation), and how to keep or improve solutions or steps to be taken for the dimension.

Data collected from all workshops were analysed using structured thematic approach (Braun and Clarke, 2006). The contributions of each participant were shared in a template that mapped against four SWOT dimensions and three sustainability aspects. The research team reviewed all the entries and grouped semantically similar items through iterative discussions. Emerging themes were validated through cross-checking with the individual expert work completed between workshops and by reviewing convergence across sessions. Items receiving independent validation from both institutions were retained as primary findings, while peripheral observations were noted as supplementary context. This process ensured that the final SWOT categories reflect a consensus view rather than the perspective of any single participant or institution.

3. Results and discussion

In this section, the findings are interpreted in relation to three bodies of literature: research on international academic cooperation, scholarship on maritime education partnerships, and sustainability frameworks applied to higher education. With respect to international academic cooperation, the SWOT profile that emerged aligns closely with patterns identified in the broader literature on inter-university alliances. Institutional complementarity, the pairing of distinct but compatible competencies, is the primary driver of sustainable academic partnerships (Knight, 2004), a dynamic clearly evident in the complementary simulation capabilities and industry networks of SAMK and AMC. At the same time, the structural barriers identified as weaknesses represent the systemic constraints associated with the governance gap in international higher education cooperation, where informal collaboration frequently precedes the formal frameworks needed to sustain that (Kehm and Teichler 2007). Specifically in the maritime education domain, the identified opportunities in both institutions' polar operations and green transition research collaboration reflect the sector-wide imperative. This aligns with the findings of Progoulaki and Theotokas (2010), which show that MET institutions must develop adaptive, internationally networked research agendas to remain relevant to an industry undergoing rapid environmental and technological transformation. The reliance on social capital as a foundational strength resonates with Donn and Al Manthri's (2010) observation that practitioner networks are the primary mechanism through which maritime education innovation is distributed across institutions. Finally, we applied Triple Bottom Line framework (Elkington, 1997b) as a normative lens that moves the analysis beyond operational efficiency. By mapping each SWOT element to a sustainability dimension, the study highlights that the most persistent threats are simultaneously economic, social, and environmental in character, reinforcing the argument that sustainable international cooperation requires integrated, rather than siloed, governance responses.

3.1. Strengths

The collaboration between SAMK and the AMC demonstrates a range of complementary strengths that contribute to sustainable development across social, environmental, and economic dimensions (Table 1). These strengths not only enhance the effectiveness of joint activities but also provide a strong foundation for long-term cooperation and capacity building.

A key strength lies in the complementary expertise of the partner institutions, particularly in the social and environmental domains. The presence of similar academic, professional, and research backgrounds enables efficient collaboration among staff, as shared knowledge bases reduce communication barriers and facilitate mutual understanding. At the same time, differences in specific areas of expertise allow for knowledge expansion and interdisciplinary development. Building common interests while strategically developing new areas of expertise ensures that collaboration remains both productive and adaptive to emerging challenges.

Table 1. Co-operation Strengths and Weaknesses of SAMK-AMC.

Strengths	**The aspect of sustainability (env., social, econ.)**	**Weaknesses**	**The aspect of sustainability (env., social, econ.)**
Complimentary expertise	social, environmental	Diverse academic systems	social
Simulation expertise and capabilities	social	Varied funding schemes	economic
Strong academic-industry relationships	social	Geographic distance, time zones	economic, social
Already having a MoU and history of collaboration	social	Inability to collaborate using the EU research fundings	economic
Joint research project	social	Potential lack of personal commitment	social
Skills on online co-work	social, economic, environmental		
Individual commitment	social		
Investing time and money in the co-operation	economic		

In addition, both institutions possess advanced simulation expertise and capabilities, particularly in the social dimension of training and education. Although their simulation infrastructures have slightly different functionalities, this diversity presents an opportunity to leverage each institution's unique strengths. By integrating these capabilities, the collaboration can enhance research outcomes, broaden data collection possibilities, and create richer training environments for students and professionals.

Strong academic–industry relationships further reinforce the partnership's social sustainability. SAMK's engagement with the Finnish Maritime Cluster and its memorandum of understanding (MoU) with Rauma Marine Construction (RMC), combined with AMC's extensive alumni network and active participation in organizations such as Maritime Industry Australia Ltd and Ports Australia, provides valuable industry connections. Expanding these networks through reciprocal engagement, such as staff exchanges, site visits, and joint industry initiatives, can significantly enhance knowledge transfer and practical relevance.

The existing MoU and established history of collaboration between SAMK and AMC provide an important structural and relational foundation. As members of the IAMU, the institutions have already engaged in joint research and educational initiatives, including staff and student mobility. The successful completion of two IAMU-funded joint research projects demonstrates both compatibility and a shared commitment to achieving common goals. These experiences can be further leveraged to pursue new opportunities, such as collaborative grant applications, research on the green transition, and studies on specialized maritime operations.

Another important strength is the opportunity to involve additional partners in order to broaden the collaboration's reach and contribute to global capacity building, particularly in alignment with United Nations Sustainable Development Goal 4 (quality education). Expanding the network of stakeholders enhances the impact and scalability of joint initiatives.

From a socio-economic and environmental perspective, the increasing effectiveness of online co-working practices represents a significant advantage. The ability to collaborate without depending on physical presence enables more rapid, flexible interaction, reducing travel-related environmental impacts while improving efficiency. However, maximizing this benefit requires deliberate development of digital collaboration skills and the adoption of structured processes.

Finally, the success of the collaboration is strongly supported by individual commitment and institutional investment. Personal connections among team members foster trust and facilitate communication, highlighting

the importance of maintaining both professional and human relationships. At the same time, both organizations are investing financial and human resources into the partnership, underscoring its strategic importance. Ensuring sustainable funding mechanisms will be essential for maintaining and expanding these collaborative efforts.

3.2. Weaknesses

Despite the strong foundation for collaboration between SAMK and the AMC, several structural and operational challenges (Table 1) may hinder the long-term sustainability of joint activities across social and economic dimensions.

One significant challenge arises from differences in academic systems, particularly regarding institutional calendars and workload structures. Misaligned semesters and teaching schedules limit opportunities for staff mobility, joint teaching, and student exchanges. These constraints reduce the flexibility required for sustained interaction and knowledge sharing. Addressing this issue requires the development of tailored mobility arrangements that accommodate the schedules of partner institutions. Flexible academic frameworks, supported by targeted provisions within memoranda of understanding (MoUs), can help facilitate more effective exchanges.

Economic challenges are also evident in the variation of funding schemes across regions. Differences in eligibility criteria and funding priorities complicate joint participation in externally funded projects. Restrictions associated with European funding mechanisms present barriers for non-European partners. For example, Australian institutions face limited participation in programs such as Horizon Europe, which constrains access to significant research funding opportunities. To mitigate this, collaboration efforts should focus on identifying and targeting funding streams that explicitly support international partnerships, as well as leveraging industry connections for sponsored research and philanthropic contributions. Additionally, programs such as Erasmus+ may provide partial support when aligned with institutional capacities. While ongoing policy developments may improve inclusion in the future, current collaboration must rely on alternative funding strategies, including national research funding and cost-sharing mechanisms between partner institutions.

Geographic distance and time zone differences further complicate collaboration. The physical separation between Finland and Australia makes frequent face-to-face meetings costly and logistically challenging, while time differences hinder real-time communication. These factors can slow decision-making processes and reduce opportunities for spontaneous interaction. However, increased reliance on digital communication tools and asynchronous collaboration methods can partially offset these limitations. Scheduling meetings alongside major international events, such as those organized by the IAMU, can also maximize the efficiency of in-person engagement.

Finally, the sustainability of collaboration is influenced by participants' individual commitment. Competing professional priorities, limited time, and varying levels of engagement can lead to delays or reduced effectiveness in joint activities. Strengthening commitment requires establishing clear, meaningful, and outcome-oriented goals that align with both institutional priorities and individual motivations. Fostering strong interpersonal relationships and maintaining regular communication are also critical to sustaining long-term social engagement.

3.3. Opportunities

The collaboration between SAMK and the AMC presents a wide range of opportunities that support sustainable development across social, economic, and environmental dimensions (Table 2). These opportunities build on existing strengths while enabling the partnership to expand its impact in education, research, and industry engagement.

One key opportunity lies in developing joint courses, which can enhance both educational quality and resource efficiency. By co-designing and co-delivering courses, the partner institutions can share expertise, reduce duplication of effort, and provide students with access to a broader range of knowledge and perspectives. Such initiatives contribute to both social and economic sustainability by improving learning outcomes while optimizing the use of institutional resources.

Table 2. Co-operation Opportunities and Threats of SAMK-AMC.

Opportunities	**The aspect of sustainability (env., social, econ.)**	**Threats**	**The aspect of sustainability (env., social, econ.)**
Joint courses	social, economic	Policy and regulatory differences in countries	social
Staff and student mobility	social	Dependence on external funding	economic
Knowledge & skills in polar regions	social	High travel costs	economic
Joint projects	economic	A carbon footprint associated with physical co-operation	environmental
Personal connection between the team members	social	Communication differences, Language differences (English vs. Finnish)	social
Reducing CO2 emissions of maritime sector to combat climate crisis	environmental	Cultural differences	social
Building up on past projects and their themes	economic	Different leadership practices	social
Joint academic publishing	economic, social	Change in position in the workplace	economic, social
Funding together from Finland-Australia	economic	Change of policies of maritime sector	environmental, social, economic
Making a strategic planning for short term-midterm-long term co-operation	economic, social		
Joint work on themes to mitigate the climate crisis	environmental		
Joint environmental projects on CO2e reductions	environmental		

Protecting nature and environment: Controlling pollution	environmental
Rescue operations	environmental

Another major opportunity arises from the complementary expertise of the two countries in polar and cold-climate maritime operations. Finland's extensive experience in icebreaker design and winter navigation, combined with Australia's strategic role in Antarctic operations and the presence of vessels such as the RSV Nuyina, provides a unique platform for joint research and training. By integrating knowledge from both contexts, the collaboration can develop a more comprehensive understanding of polar maritime challenges and solutions.

The partnership is also well-positioned to expand joint research activities. Building on previous successful collaborations, new projects can focus on emerging priorities such as maritime decarbonization, digitalization, and operational efficiency. These efforts can lead to increased academic output, including joint publications, and to enhanced access to international funding opportunities. Coordinated funding applications involving both Finnish and Australian stakeholders can further strengthen the collaboration's economic sustainability.

Environmental sustainability represents a particularly important area of opportunity. Joint initiatives to reduce greenhouse gas emissions in the maritime sector align closely with global climate goals. Research on topics such as alternative fuels, electrification, and operational optimization can contribute to the green transition. For instance, analysing the performance of Finnish-built vessels in Australian conditions, as well as collecting data from battery-powered ferries, can provide valuable insights for reducing emissions. These efforts support broader climate objectives, including those promoted by the United Nations.

In addition to emissions reduction, the collaboration can address wider environmental challenges, such as marine pollution and ecosystem protection. Through joint educational and research activities, the partner institutions can develop expertise and solutions that support sustainable maritime operations. Furthermore, cooperation in areas such as maritime safety and rescue operations offers opportunities to enhance both environmental protection and operational resilience.

Finally, developing a structured strategic plan for short-, medium-, and long-term collaboration is essential to maximizing these opportunities. Existing industry links, such as those related to the construction and operation of vessels like the Spirit of Tasmania ferries, demonstrate the potential for deeper academia–industry cooperation. Strengthening these connections can facilitate applied research, innovation, and knowledge transfer.

3.4. Threats

While the collaboration between SAMK and the AMC demonstrates strong potential, several external threats may affect its long-term sustainability across social, economic, and environmental dimensions (Table 2). These threats are largely systemic and require proactive management to mitigate their impact.

One significant challenge is differences in national policies and regulatory frameworks. Variations in higher education systems, research governance, and maritime regulations between Finland and Australia may create barriers to effective cooperation. These differences can affect project implementation, funding eligibility, and operational practices. To address this, it is essential to maintain continuous review and mutual understanding of relevant policies, identify areas of alignment, and develop strategies to navigate regulatory discrepancies.

A major economic threat is the collaboration's dependence on external funding. Limited or inconsistent access to financial resources can delay or even halt joint activities. This risk is particularly relevant in the context of international research funding, where competition is high, and eligibility criteria vary. Maintaining agile operational models and actively pursuing diverse funding sources, including governmental, industrial, and institutional streams, will be critical to ensuring continuity.

High travel costs and geographic distance also pose significant economic constraints. Long-distance travel between partner institutions increases the financial burden associated with face-to-face meetings, workshops, and mobility activities. These challenges are closely linked to environmental concerns, as frequent travel contributes to increased greenhouse gas emissions. Reducing reliance on physical travel by prioritizing virtual

collaboration, while strategically aligning necessary in-person meetings with major events such as those organized by the IAMU, can help mitigate both economic and environmental impacts.

Communication and language differences present additional social challenges. Although English serves as the primary working language, differences in terminology, interpretation, and communication styles may lead to misunderstandings. These issues can be addressed through deliberate clarification practices, verification of key concepts, and an openness to learning from different linguistic perspectives.

Cultural differences, including variations in work practices, attitudes, and relationships with industry, may also influence collaboration. Similarly, differences in leadership styles and decision-making processes, such as timelines, responsibilities, bureaucracy, and organizational hierarchies, can create friction if not properly managed. Encouraging cultural exchange, fostering mutual respect, and facilitating regular dialogue between leadership teams are essential strategies for overcoming these challenges.

Another potential threat arises from personnel changes. Staff turnover, role changes, or retirement can disrupt continuity and weaken established relationships. To reduce this risk, it is important to implement overlapping roles and knowledge-sharing mechanisms that preserve institutional memory and ensure collaboration is not dependent on selected individuals.

Finally, evolving policies within the maritime sector itself may impact the direction and relevance of joint activities. Shifts in industry priorities, such as changes in environmental regulations or technological focus, could create misalignment between partners if not closely monitored. Continuous engagement with national authorities and international regulatory bodies, including the International Maritime Organization (IMO), will be essential to anticipate and respond to these changes.

3.5. Practical Guidance for Sustainable International Cooperation Among IAMU Member Universities

For member institutions of the IAMU, effective international cooperation requires a structured, sustainability-oriented approach. Building on the principles of leveraging strengths, addressing weaknesses, exploiting opportunities, and mitigating threats, this guidance outlines practical actions across short-, mid-, and long-term horizons. The aim is to ensure that IAMU collaborations remain socially, economically, and environmentally sustainable.

In the short term (1-2 years), institutions should focus on understanding their collaborative potential and enabling efficient interaction. First, universities must identify and map their strengths, including academic expertise, simulation capabilities, and industry connections. Transparent communication of these strengths allows partners to quickly identify areas of alignment and synergy. At the same time, efforts should be made to minimize operational weaknesses, particularly those related to misaligned academic calendars, communication barriers, and limited access to funding. Practical steps include flexible mobility arrangements, clear communication protocols, and the use of digital collaboration platforms to reduce dependency on physical meetings. Institutions should actively capitalize on immediate opportunities, such as developing pilot joint courses, initiating small-scale research projects, and promoting staff and student exchanges. These activities build trust and demonstrate early value. Finally, it is essential to manage immediate threats, including high travel costs and carbon emissions. Prioritizing virtual collaboration and aligning physical meetings with existing events (*e.g.*, IAMU conferences) can reduce both financial and environmental burdens.

In the mid-term (3–5 years), the focus should shift toward scaling and institutionalizing cooperation. Universities should deepen and integrate their strengths by establishing joint research themes, shared teaching programs, and coordinated use of infrastructure such as simulation facilities. This phase should emphasize interdisciplinary collaboration and capacity building. To further eliminate persistent weaknesses, institutions should formalize cooperation through updated agreements, harmonized academic structures where possible, and dedicated administrative support for international projects. Diversifying funding sources through national, international, and industry partnerships becomes increasingly important. Opportunities should be expanded strategically, including larger joint research initiatives, co-authored academic publications, and broader engagement with industry stakeholders. Emphasis should be placed on sustainability-related themes such as decarbonization, digitalization, and maritime safety. At the same time, institutions must actively manage evolving threats, including policy changes, funding uncertainties, and cultural differences. Regular strategic

dialogue, leadership engagement, and monitoring of global maritime trends (*e.g.*, through bodies such as the International Maritime Organization) are essential.

In the long term (beyond 5 years), IAMU member universities should aim to position their collaboration as a model for sustainable global partnerships. Institutions should fully leverage their combined strengths to create globally recognized centers of excellence in maritime education and research. This includes sustained joint programs, long-term research platforms, and integrated academic–industry ecosystems. Efforts to eliminate structural weaknesses should result in seamless collaboration frameworks in which mobility, funding, and administrative processes are no longer barriers but enablers. Opportunities should be maximized at scale, including leadership in global sustainability initiatives, contributions to international policy development, and active support for capacity building in developing regions, aligned with the United Nations' goals. Finally, long-term resilience depends on the ability to anticipate and mitigate systemic threats, such as geopolitical changes, environmental crises, and shifts in the maritime sector. Building adaptable, well-funded, and institutionally embedded partnerships ensures continuity despite external uncertainties.

While the empirical basis of this study is the SAMK–AMC partnership, the guidance developed here is intended to be broadly applicable across the IAMU network and beyond. The SWOT framework is inherently independent of institutions: the categories of strengths, weaknesses, opportunities, and threats identified in this case are not unique to a Finland-Australia pairing but reflect structural conditions common to many cross-regional academic collaborations. Funding asymmetries, regulatory divergence, and the social capital dependency identified here are well-documented features of inter-university partnerships in general (Knight, 2004; Kehm & Teichler, 2007), which supports the transferability of the findings to other institutional dyads. We are not claiming that the results are transferable to all institutions; however, IAMU member universities can use this case as an exemplar of a successful pairing. In doing so, it needs to be considered that IAMU member universities span a wide range of institutional contexts, from large research-intensive universities to specialized maritime academies in developing economies; thus, the relative weight of each SWOT element will vary accordingly. The practical guidance offered in this section is therefore best understood as a modular framework: institutions are encouraged to apply the SWOT-TBL mapping tool to their own bilateral context, calibrating the short-, mid-, and long-term actions to their specific resource base, regulatory environment, and strategic priorities. In this way, the SAMK-AMC case serves as an illustrative reference point rather than a prescriptive template.

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Psychological Well-Being and Welfare Needs of Georgian Seafarers. A Cross-Sectional Survey Study

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Abstract: As a cornerstone of global trade, the maritime industry depends on the well-being of seafarers. However, their psychological health is often overlooked. This study provides an empirical, regionally specific analysis of Georgian seafarers. Using a cross-sectional survey, the study assesses the psychological state and well-being of active Georgian maritime professionals. The findings reveal that respondents experience stress, loneliness, and anxiety, primarily due to prolonged separation from family. The data underscores the seafarers' desire for improved welfare provisions, such as reliable internet access, a variety of recreational activities, and more frequent shore leave. This survey establishes a vital foundation for addressing morale challenges. It emphasizes the importance of collaboration between shipping companies and Georgian maritime authorities to improve onboard living conditions and support services. Ultimately, these findings inform strategies to enhance retention and operational safety within the Georgian maritime sector by addressing the workforce's specific psychological and welfare needs.

Keywords: psychological well-being; maritime welfare; occupational stress; family separation

1. Introduction

The global maritime industry is the backbone of international commerce. It transports approximately 90% of world trade across the oceans (Allianz Commercial, 2025). This enterprise relies on an estimated workforce of over 1.8 million seafarers worldwide (BIMCO and ICS, 2021). Seafarers face daily professional challenges that test their psychological resilience due to their unique working and living conditions . Prolonged physical isolation, separation from family, hierarchical environments aboard ships, difficulties related to cross-cultural interactions, and limited opportunities for rest and healthcare create stressors that significantly impact on a seafarer's mental health and professional performance (Brooks and Greenberg, 2022; Carotenuto et al., 2012; Iversen, 2012).

A growing body of international research confirms that seafarers face a higher risk of stress, anxiety, depression, and burnout than other professional groups (Jonglertmontree et al., 2022; Nittari et al., 2022). Family separation and loneliness are the most consistently reported psychological stressors. These stressors are exacerbated by limited communication capacity at sea and the socially isolating nature of shipboard life (Abadicio et al., 2025; Brooks and Greenberg, 2022; McVeigh et al., Mellbye and Carter, 2017, 2019; Oldenburg and Jensen, 2019; Sampson and Ellis, 2021). The psychological state and well-being of seafarers can be negatively affected by the attitude of onboard leadership, the fair distribution of work duties, and the willingness of other crew members to provide support (Ajayi and Udeh, 2024; Karakasnaki et al., 2025). Post-pandemic data further indicate that a significant proportion of seafarers continue to experience deteriorating mental health and express dissatisfaction with their welfare, rest infrastructure, and access to qualified medical assistance (Pauksztat, Andrei, and Grech, 2022; Onakpojeruo et al., 2023; Sampson et al., 2025).

Oldenburg, Baur, and Schlaich (2010) characterized seafaring as an occupation beset by a distinct cluster of physical, physiological, and psychological risks that interact in complex and often compounding ways. Living in confined spaces, working irregular hours, facing unpredictable weather, being exposed to hazardous cargo, and dealing with the constant possibility of emergency situations creates a chronic, low-level threat environment that is cognitively and emotionally taxing. A landmark systematic review by Brooks and Greenberg (2022) synthesized evidence from 63 studies and confirmed that seafarers experience higher rates of anxiety, depression, post-traumatic stress disorder (PTSD), and suicidal thoughts than the general population.

Mental health outcomes were found to be influenced by organizational and relational factors, including leadership quality, perceived fairness, and the strength of social support networks. Carotenuto et al. (2012) identified cultural transitions, loss of established social roles, and disruption of circadian rhythms as potent stressors. Iversen (2012) argued that psychological distress directly endangers maritime safety by impairing decision-making and increasing the risk of accidents.

Contract durations ranging from three to nine months, coupled with limited and unreliable communication, can lead to acute and chronic loneliness, relationship strain, and significant parental guilt, particularly among seafarers with dependent children. Jonglertmontree et al. (2022) conducted a scoping review of 25 studies and identified family separation and loneliness as the most frequently cited mental health risk factors. While the digital communication revolution has mitigated some of these challenges, access to reliable, high-speed internet is inconsistent across vessels and geographic regions. Limited free time also constrains the frequency and quality of meaningful family communication. Sampson et al. (2025) documented persistent dissatisfaction with connectivity provisions, identifying it as a primary concern among cargo seafarers.

Contemporary merchant shipping relies heavily on multinational crews, which bring individuals of diverse cultural, linguistic, religious, and ethnic backgrounds into sustained contact within confined environments on vessels. Language barriers, divergent cultural norms, and differential exposure to racialized attitudes moderate crew cohesion and individual well-being (Oldenburg, Baur, and Schlaich, 2010). Fernandez et al. (2018) emphasized that Filipino seafarers often conceptualize depression through interpersonal and somatic lenses, which contrasts with Western clinical frameworks. Lee et al. (2022), on the other hand, identified systemic discrimination and a lack of language support as key psychosocial stressors for foreign seafarers.

Sampson et al. (2020) highlighted that while religious faith provides a crucial psychological "solace" for migrant workers, seafarers often suppress their spiritual practices to maintain interpersonal harmony in the confined shipboard environment. Cadge et al. (2023) further observed that port chaplains provide a vital form of "spiritual agency," offering seafarers a sense of connection to a higher power that serves as a buffer against the regimented nature of life at sea. Nittari et al. (2022) identified crew interpersonal dynamics and cultural adaptation difficulties as significant contributors to psychological stress, particularly for seafarers who are numerical minorities within crews.

Karakasnaki et al. (2025) demonstrated that perceptions of well-being onboard vary significantly by company size and vessel type, indicating that organizational and structural characteristics mediate the social environment experienced by individual seafarers.

Ajayi and Udeh (2024) advocated for a systemic approach that considers mental health an integral part of operational risk management. Meanwhile, Abadicio et al. (2025) discovered that informal peer support was the most common coping mechanism, while formal mental health services were underutilized due to stigma and limited accessibility.

The Maritime Labour Convention, 2006 (MLC, 2006) establishes minimum standards for seafarer welfare, including access to medical care, adequate housing, nutritious food, recreational facilities, and shore leave. However, there are significant discrepancies between formal entitlements and practical experiences, as documented by Karakasnaki et al. (2025).

Against this backdrop, Georgia has established itself as a significant contributor to the global maritime labor market. Despite Georgian-certified seafarers' strong reputation for professionalism and adaptability, empirical research dedicated specifically to their psychological well-being remains sparse. This study is the first empirical attempt to address the psychological conditions and welfare needs of Georgian seafarers. A significant contextual milestone was Georgia's accession to the Convention (MLC, 2006) in 2020. However, the extent to which these standards are experienced by Georgian seafarers has not yet been systematically studied.

The research was conducted from November to December of 2024. The purpose-built questionnaire was developed based on a systematic review of the maritime welfare literature and covered five thematic domains: Personal and Professional Background; Life at Sea: Adaptation and Challenges; Life on Shore: Relationships and Social Integration; Support Systems and Professional Development. The final instrument contained 31 closed (single- and multiple-response) and 3 open-ended items. Questions with multiple-response options are indicated in the relevant tables, percentages therefore exceed 100% where applicable. The questionnaire was distributed via maritime professional networks, crewing companies, and social media, resulting in 307 valid

responses from active Georgian seafarers. The study aimed to characterize the demographic and professional profiles of the respondents, identify psychological stressors encountered during service and upon return to shore, assess the quality of social and intercultural interactions aboard ships, and evaluate self-reported coping capacities and expectations for onboard welfare improvements. Participation was entirely voluntary and anonymous and conducted in accordance with institutional ethical guidelines at Batumi State Maritime Academy. Quantitative data were analyzed using descriptive statistics, including frequency distributions and percentage calculations. Open-ended responses were thematically coded to contextualize findings regarding elevated psychological risks.

2. Results

The age distribution revealed a predominantly middle-career workforce: 48.2% (n = 148) fell within the 26–35 age bracket, followed by 21.2% (n = 65) aged 36–45, 16.3% (n = 50) aged 18–25, 10.7% (n = 33) aged 46–55, and 3.6% (n = 11) aged 56–65 (see Table 1).

Table 1. Age distribution of respondents.

Age Group	n	%
18 – 25	50	16.3
26 – 35	148	48.2
36 – 45	65	21.2
46 – 55	33	10.7
56 – 65	11	3.6

In terms of family status, 61.6% (n = 189) were married. A substantial proportion of respondents had parental responsibilities: 14.0% had one child, 27.7% had two, and 10.1% had three or more. Professional experience varied: the largest category was 1–5 years (32.2%, n = 99), followed by 15–30 years (19.5%, n = 60), 5–10 years (17.6%, n = 54), and 10–15 years (14.0%, n = 43) (see Table 2).

Table 2. Years of seafaring experience.

Experience Category	n	%
Novice (first sea service)	27	8.8
1–5 years	99	32.2
5–10 years	54	17.6
10–15 years	43	14.0
15–30 years	60	19.5
Other (specified individually)	24	7.8

The range of respondents included all major ranks. Watchkeeping officers (deck) were the largest group (26.4%, n = 81), followed by ship masters (10.7%, n = 33) and cadets (10.1%, n = 31). The most reported vessel type was oil tankers (48.9%, n = 150), followed by chemical tankers (25.7%, n = 79) and bulk carriers (11.7%, n = 36).

Overall, environmental adaptation was positive. 52.1% (n = 160) reported adapting easily, while 45.9% (n = 141) indicated that adaptation depended on the specific ship and crew composition. Only 1.0% (n=3) reported adapting with difficulty. This conditional pattern, in which nearly half of all seafarers link their adaptive capacity to environmental and relational circumstances, has important implications for the design of crew welfare interventions and crewing policies. This finding has important implications for crew welfare interventions.

The most frequently cited challenges at sea were cultural differences (32.9%, n = 101), lack of internet and communication resources (31.9%, n = 98), and emotional and psychological burden (26.7%, n = 82). 26.7% (n=82) selected "all the above", indicating that a substantial subgroup experiences the full spectrum of challenges concurrently Safety and emotional support deficiencies were reported by 13.4% (n=41), and isolation and communication restrictions by 10.7% (n=33) (see Table 3, multiple responses possible, so the sum of the percentages was greater than 100%).

Table 3. Principal challenges faced at sea.

Challenge	n	%
Cultural differences and adapting to them	101	32.9
Lack of internet and communication means	98	31.9
Emotional and psychological burden	82	26.7
Safety and emotional support deficits	41	13.4
Isolation and communication restrictions	33	10.7
All the above	82	26.7

Self-assessed intercultural communication competence was markedly high: 97.1% (n=298) rated their interactions with crew members of different ethnic backgrounds positively, citing respect for cultural diversity, emotional intelligence, and professional skills as enabling factors. Only 2.0% (n=6) characterized these interactions negatively. However, more nuanced questioning revealed that 16.9% (n = 52) identified language barriers, 12.1% (n = 37) identified social differences, and 7.2% (n = 22) identified ethnic tensions as specific difficulties.

Georgian-to-Georgian interactions received the highest ratings for pleasant social interactions (78.8%, n = 242), followed by interactions with Filipino seafarers (48.9%, n = 150). Indian seafarers were most frequently mentioned in the context of unpleasant interactions (38.1%, n = 117), followed by Russian (29.3%, n = 90) and Ukrainian (27.0%, n = 83) seafarers. These patterns echo findings from other multinational crew studies on nationality-based social clustering aboard ships. However, as self-reported data, they likely reflect a range of contextual, linguistic, hierarchical, and geopolitical factors, such as shared language with the respondent group, relative rank or seniority on board, and broader political relations between countries of origin, rather than fixed traits of any national group. The findings should therefore not be read as evidence that seafarers of a given nationality are inherently more or less pleasant to work with. rather, they point to structural and situational dynamics in multinational crew relations that merit further, more targeted investigation.

Over half of Georgian seafarers (54.9%) experienced some degree of relationship strain due to maritime service. 32% (n = 99) acknowledged a partial negative impact on family relationships, 15.3% (n = 47) confirmed a definite negative effect, and 7.5% (n = 23) reported occasional difficulties. The main barriers to family communication were technical limitations and a lack of internet connectivity (46.6%, n = 143), time zone differences (32.6%, n = 100), and limited free time (21.5%, n = 66) (see Table 4, respondents could select more than one option, so the sum of the percentages was greater than 100%).

Table 4. Barriers to maintaining communication with family while at sea.

Barrier	n	%
Technical limitations / lack of internet	143	46.6
Time zone differences	100	32.6
Limited free time	66	21.5
All the above	98	31.9

Upon returning to shore, respondents identified the transition from shipboard life to family life as the most common social challenge (42.3%, n = 130). This was followed by financial difficulties (19.5%, n = 60) and the degradation of personal relationships (15.0%, n = 46). Although 56.4% (n = 173) reported never experiencing reintegration difficulties, 42.3% acknowledged facing occasional challenges. The most common coping strategies were communicating with family and friends (48.9%, n = 150) and resting to recharge (35.5%, n = 109).

Separation from family was by far the most frequently selected welfare issue, endorsed by 56.4% (n = 173) of respondents. This was followed by "all the above" (26.4%, n = 81), lack of rest and vacations (24.1%, n = 74), and stress and psychological health (21.2%, n = 65) (see Table 5, respondents could select more than one option, so the sum of the percentages was greater than 100%).

Table 5. Most significant issue for seafarers, according to respondents.

Issue	n	%
Separation from family	173	56.4
Lack of rest and vacations	74	24.1
Stress and psychological health	65	21.2
Working conditions and social relationships	48	15.6
Isolation	46	15.0
Restriction of personal life	45	14.7
All the above	81	26.4

The overwhelming prominence of family separation in this ranking is consistent with the international evidence base and underscores its primacy as a welfare intervention target (Brooks and Greenberg, 2022, Jonglertmontree et al., 2022).

Most respondents (84.7%, n = 260) self-assessed their psychological preparedness as adequate, though this high rate may reflect social desirability bias in a professional culture that discourages acknowledging psychological vulnerability. This pattern has been noted in the broader literature on seafarers' mental health (Abadicio et al., 2025; Iversen, 2012).

Leisure activities were widely endorsed as effective stress management tools. 45.9% (n = 141) reported that they helped completely, and 48.5% (n = 149) reported that they helped somewhat. Respondents cited communication improvement programs (58.0%, n = 178) as the primary onboard conflict resolution mechanism. Meanwhile, formal mental health programs were utilized by only 31.6% (n = 97).

Shore-based activities currently practiced by respondents were led by time with family and friends (74.9%, n=230), travel (45.0%, n=138), sports and physical activity (43.0%, n=132), courses and new skill development (30.6%, n=94), and cultural and social events (17.3%, n=53). The centrality of family time as a shore activity mirrors its primacy as a psychological stressor when absent during service.

Willingness to participate in social activities or programs organized for seafarers was high: 77.5% (n=238) expressed readiness to participate, while 19.5% (n=60) declined. Among preferred activity types, social events and team activities (56.0%, n=172), personal development events (45.0%, n=138), and cultural and educational events (40.1%, n=123) were most frequently endorsed.

Satisfaction with the performance of crewing companies operating in Georgia was mixed: 36.8% (n=113) expressed satisfaction, 24.4% (n=75) dissatisfaction, and 28.0% (n=86) were unable to rate performance because they were employed through foreign intermediary companies rather than domestic crewing agencies. This distribution signals meaningful room for improvement in the quality and regulation of domestic crewing services (see Table 6).

Regarding institutional representation, 44.6% (n=137) reported having had no contact with any Georgian seafarers' union, 25.4% (n=78) had been in contact, and a notable 25.7% (n=79) could not assess the union because they lacked information about it. This combined majority (70.3%) without meaningful union

engagement points to a significant gap in institutional representation and outreach within the Georgian maritime sector.

Table 6. Satisfaction with Georgian crewing companies.

Response	n	%
Satisfied	113	36.8
Not satisfied	75	24.4
Cannot rate (employed by foreign intermediary)	86	28.0
Other	33	10.7

The prospect of establishing a dedicated seafarers' association in Georgia attracted support from 86.3% (n=265) of respondents, with only 1.3% (n=4) opposed. A further 7.5% (n=23) expressed skepticism about the likelihood of meaningful change, and 4.2% (n=13) indicated indifference. This overwhelming endorsement reflects a pent-up demand for institutional representation, advocacy, and coordinated welfare delivery within the Georgian maritime community.

3. Discussion

The findings of this study are broadly consistent with international literature on the psychological burden of maritime employment. Family separation, identified as the most significant welfare issue by 56.4% of respondents, remains the defining challenge for Georgian seafarers, consistent with international literature (Abadicio et al., 2025; Brooks and Greenberg, 2022; Jonglertmontree et al., 2022). Although a significant proportion of respondents reported feeling prepared to handle psychological demands and affirmed the restorative value of leisure activities, a substantial proportion reported emotional and psychological burden as a primary sea-based challenge (26.7%) and acknowledged at least a partial negative impact on family relationships (47.6%, n = 146). These figures must be considered in the context of potential social desirability biases in a professional culture that values stoicism (Abadicio et al., 2025; Iversen, 2012).

The conditional nature of environmental adaptation, reported by 45.9% of respondents as dependent on the specific ship and crew, highlights the extent to which psychological well-being is shaped by the immediate social and organizational environment. Thus, crew composition, leadership quality, and organizational culture emerge as modifiable determinants of seafarer well-being, offering concrete leverage points for intervention (Brooks and Greenberg, 2022; Karakasnaki et al., 2025). A critical, structurally tractable source of distress is inadequate connectivity. Technical limitations were the most frequently cited barrier to family communication (46.6%), and internet deficits were among the top two specific challenges at sea (31.9%). Therefore, improving internet connectivity on vessels employing Georgian seafarers should be a central demand in any Georgian maritime welfare strategy, as it is the most structurally remediable dimension of family separation distress (Jonglertmontree et al., 2022; Sampson et al., 2025).

The self-reported intercultural communication competence of Georgian seafarers was remarkably high. 97.1% characterized their interactions with multinational crew members positively. This finding may reflect genuine cultural adaptability and professional socialization within an internationally oriented workforce. It is consistent with the positive portrayal of Georgian maritime professionals in industry commentary (SAFETY4SEA, 2023). However, the same data reveal a degree of nationality-based social differentiation in positive and negative interaction patterns consistent with broader findings on the importance of national identity as an organizing principle in multinational crews (Oldenburg and Jensen, 2019).

The coexistence of high self-assessed intercultural competence (97.1%) and the identification of cultural differences as the most frequently cited seafaring challenge (32.9%) is not paradoxical. Rather, it suggests that Georgian seafarers have developed effective interpersonal skills for managing intercultural encounters. However, the sustained cognitive and emotional effort required constitutes a significant psychological burden, one that welfare interventions should explicitly acknowledge (Nittari et al., 2022). The low level of meaningful union engagement (70.3%) and the near-unanimous support for a dedicated Georgian seafarers' association

(86.3%) are the study's clearest policy-relevant findings. Such an association could amplify the collective voice of Georgian seafarers, provide access to welfare services and mental health support, coordinate labor representation, monitor MLC compliance, and serve as a hub for shore-based programming (Ajayi and Udeh, 2024). The relatively low utilization of formal mental health programs (31.6%) reflects broader patterns of stigma and structural barriers. In the Georgian maritime context, embedding mental health literacy within existing training and communication programs, rather than positioning it as a separate clinical service, is likely to be a more effective approach (Abadicio et al., 2025).

The study has several limitations. First, the questionnaire was purpose-built for this exploratory study and was not subjected to formal psychometric validation (e.g., Cronbach's α, confirmatory factor analysis), and the use of convenience sampling precludes strict probabilistic generalization. Second, the cross-sectional design precludes causal inference. Third, the survey is susceptible to social desirability bias in self-report measures. Despite these limitations, the sample of 307 respondents, which encompasses all major ranks, vessel types, and experience levels, provides substantively informative and nationally relevant empirical findings.

4. Conclusions

This study is the first to empirically examine the self-reported perception of psychological burden, psychological well-being and welfare needs of Georgian seafarers. The findings confirm that they experience the same general constellation of psychological stressors identified in international literature, primarily family separation, communication barriers, intercultural challenges, and limited recreational and health resources, while also providing regionally specific context and empirical depth.

Several conclusions and recommendations emerge from the data:

1. Family separation and connectivity require priority investment. The identification of separation from family as the single most significant welfare issue by 56.4% of respondents, combined with the significant role of internet connectivity deficits as barriers to family communication, establishes the provision of enhanced connectivity as the most impactful actionable solution available to shipowners, leadership, and flag-state regulators. This should be treated as a welfare standard rather than a discretionary amenity.

2. Leisure and onboard quality of life are matters of welfare, not luxury. The nearly universal endorsement of leisure activities as stress reducers supports substantial investment in onboard recreational facilities. These facilities should be viewed as direct contributors to mental health, operational performance, and crew retention.

3. A Georgian seafarers' association should be established. The overwhelming support (86.3%) for a national seafarers' association, combined with the documented lack of union engagement and crewing company oversight, provides a strong basis for creating a professional organization that could provide representation, services, and regulatory advocacy.

4. Mental health support must be destigmatized and integrated. Relatively low participation in formal mental health programs indicates the necessity of incorporating destigmatized mental health literacy into the Georgian maritime training and welfare framework. Models that incorporate psychological well-being into safety culture, peer support, and routine training are likely to be more effective than clinical service models.

5. Strengthening the governance of the crewing sector is necessary. The mixed satisfaction rates with domestic crewing companies and the significant proportion of seafarers working outside of domestic regulatory frameworks indicate the need for enhanced oversight and quality standards. This can be achieved by leveraging Georgia's obligations under the MLC, 2006, as a normative foundation.

Addressing the psychological well-being and welfare needs of Georgian seafarers is an ethical imperative and strategic necessity. A psychologically healthy, well-supported, and institutionally represented Georgian maritime workforce is more resilient, productive, safer, and better positioned to sustain Georgia's valuable contribution to global maritime operations in the long term.

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Perceived knowledge growth in higher education: using students' self-reported competencies as a didactic element

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Abstract: Maritime Education and Training contributes to the long-term operational viability of maritime transportation. The paper presents an update of the didactic concept of the International Maritime Management, MSc distance degree course, namely the use of students' self-reported competencies as a didactic element in higher education. This method follows Hattie's (2009) statistical approach of visible learning whereby didactic elements are compared quantitatively. A case study design method is used to illustrate a more general principle. The concept of the distance learning degree course is introduced; subsequently, empirical data relevant to this context were collected, evaluated, and analysed. Results in terms of calculated effect sizes (d = 1.70) highlight the usefulness of the adopted methodology as they improve the learning modules from students' perspectives. Additionally, the results bear potential in terms of transferability to other universities as the concept could serve as a guideline or blueprint for the transferability across the maritime community for modification and development of study programmes.

Keywords: higher education; lifelong learning; distance education; visible learning; maritime education and training

1. Introduction

The international shipping business transports more than 80 per cent of the global trade by volume (UNCTAD, 2023). The industry relies on nearly two million seafarers who work on the merchant fleet with some 112,500 ships (approximately 65,500 ships thereof resemble the world cargo fleet) and thereby ensure international trade, namely bringing us goods and fuels (BIMCO, 2026; Clarksons Research, 2025, p. 128). The most important drivers of change in the shipping industry in 2025 and beyond are intensified climate change impacts and decarbonisation efforts, heightened geopolitical tensions, digitalisation and automation, cyber security as well as diversity (UNCTAD, 2025; Stopford, 2022).

The article promotes the topic of "Human-centered digital oceans: Educating safe & green global maritime professionals". Accordingly, maritime education and training (MET) should go beyond the education of STCW certified ratings and officers and consider further education approaches for seafarers which are in line with their demands. Therefore, this paper promotes distance learning approaches which complement high levels of flexibility but at the same time entail high demands on the participants. Therefore, the article analyses the importance of visible learning (Hattie, 2009) in MET. In addition, it is of utmost importance to clearly define learning outcomes, course descriptions as well as required knowledge and skills that are needed prior learning (Lee and Choi, 2010). Based on this, the following research question is in focus (mainly from seafarers' perspective): Which effect does visible learning in terms of didactic elements have on the improvement of further distance learning opportunities for seafarers?

The article starts with the introduction which is followed by a literature review on related work and definitions (chapter 2). The following chapter 3 presents a case study, which includes the presentation of the research method, in this case namely the concept of the International Maritime Management, MSc distance degree course and its learning modules, the collection and analysis of some empirical data as well as the discussion of the results/findings. The article finishes with a summary, conclusion and outlook.

Although single aspects of this text were discussed earlier (John et al., 2018), this study goes beyond as it provides an update and constitutes an expansion of aforementioned works. Other members of the International

Association of Maritime Universities (IAMU) may take advantage of the findings. In addition, this article opens up opportunities for cooperation as well as further works across the MET community which shares a common understanding, for example, in terms of the Global Maritime Professional Body of Knowledge (IAMU, 2019).

2. Literature review

2.1. Maritime education and training

The shipping industry has always been labour-intensive but traditionally employed rather a largely unskilled workforce. Over the time, the maritime sector has experienced a massive transformation. Changes are driven by effects of mega trends (see above). However, today it is not only external factors which impact the education of a qualified workforce but also seafarer wellbeing to an increasing extent which further intensifies the need for a transformation as well as the appeal of maritime careers in the long-term (BIMCO, 2026; n.d.; Mission to Seafarers, 2025). In line with this, MET developed further and underwent an academisation. The leading maritime universities form a global network (IAMU, 2019). The focus of the MET community has always been on the education of STCW certified seafarers (International Convention on Standards of Training, Certification and Watchkeeping for Seafarers) for all positions from ratings to officers and up to deck and engine department heads who ensure the safe and efficient operation of ships worldwide. In addition, in many MET institutions we find an increasing number of undergraduate as well as postgraduate maritime degree courses which go beyond and not only lead to STCW certificates. More and more maritime professionals achieve university degrees at IAMU member universities in order to keep up with further developments in the maritime sector. It is very likely that the demands on staff competencies will continue to increase as a result of anticipated developments (see above). This refers to tasks and work routines on ships as well as on land with regard to the organisation of transport chains in a field of tension characterised by legal, ecological, economic and social factors. In addition, a higher level of education leads to greater self-efficacy, which in turn has a positive impact on how crew members cope with challenges of life and work at sea, for example, isolation or being far away from families and friends while spending months at sea, and thus on job satisfaction (Mission to Seafarers, 2025).

2.2. Lifelong Learning and distance education

The European Commission (2001) defines Lifelong Learning (LLL) as "*all learning activity undertaken throughout life, with the aim of improving knowledge, skills and competences within a personal, civic, social and/or employment-related perspective.*" (p. 9, emphasis in original) In line with this, people learn from childhood to beyond their working life and they learn not only in so-called formal educational programmes but also outside of university contexts, especially in the workplace and in social environments. The goals of LLL are diverse and they aim to improve employability, reskill and upskill people in a changing world, enable participation in education, as well as strengthen self-directed learning, among other things. All such activities facilitate people in order to keep up with developments, master the digital revolution or contribute to a greener future. Moreover, concepts of LLL address the improvement of well-being and health (UNESCO, 2025; OECD, 2023). These arguments are in line with the demands in the maritime sector and MET (see above) but also associated with the Sustainable Development Goals (SDG), especially SDG 4: Quality Education and SDG 5: Gender equality (UN, n.d.).

The next step is to translate the basic ideas of LLL into operational concepts. Therefore, the focus of this paper is on distance learning degree courses as such programmes are also suitable to consider the peculiarities of seafarers as lifelong learners. The following factors characterise maritime professions at sea: seafarers have long, irregular and alternating periods of sea time and vacation and they sail in different and changing time zones with limited access to the Internet while at sea (Nause et al., 2018). According to a common definition, distance education is described as "*institution-based, formal education where the learning group is separated, and where interactive telecommunications systems are used to connect learners, resources, and instructors.*" (Simonson, 2009, cited in Simonson and Seepersaud, 2019, p. 1, emphasis in original)

2.3. Visible Learning

The term refers to a meta-analysis carried out by John Hattie (2009), whereby 138 different influencing contributors on educational outcomes are compared quantitatively. All influencing contributors or effects analysed follow a normal distribution. The average effect size is $d = 0.4$ and it is referred to as the typical effect or the 'hinge-point' (pp. 15–18). In this context, it is noteworthy that "[…] those students who do not achieve at least a 0.40 improvement in a year are going backwards […]" (p. 250). The success of all effects is judged relative to the hinge-point and these results help to analyse which measures work best in education. The key message is: make teaching and learning visible. Teachers know the intended outcomes, activities and assessment as well as success criteria of their learning modules. The aim is that these factors follow a cohere concept (Biggs, 1996) and teachers communicate it to the learners in the best way possible. Moreover, shift the focus to what students are learning instead of focussing on what teachers are teaching. It is of utmost importance that lecturers follow an educational paradigm which puts the learners' perspective to the fore and considers feedback which creates opportunities for users to reflect on their progress and exchange ideas. Key questions are: what works best (for whom) and why? But also: for whom does it not work?

With a reported effect size of Cohen's $d = 1.44$ (Cohen, 1988) 'self-reported grades' are the highest ranked didactic element or influencing contributor in the zone of desired effects of the visible learning meta-analysis (Hattie, 2009, p. 43 f.). Accordingly, learners know very precisely what they are capable of, what they have achieved in terms of learning, as well as their chances of success in terms of assessment. Based on previous learning experiences but also prior knowledge in the context of LLL, learners can self-assess their performance level relatively accurately.

Later, Hattie analysed further factors and updated his list to 195 effects (Hattie, 2015). Here, the 'collective teacher efficacy' reaches even a higher effect ($d = 1.57$). It is about the collective belief of the teachers of the institution in their ability to teaching and especially positively affecting students' learning. In other words, when the teacher group (its members) believes that they can make a positive difference it is very likely that they will do so. The idea of this 'new number one' is older and refers to the concept of self-efficacy by Bandura (1993; 1997) who defines perceived collective efficacy as "*a group's shared belief in its conjoint capabilities to organize and execute the courses of action required to produce given levels of attainments.*" (1997, p. 477, emphasis in original)

3. Case study: International Maritime Management

3.1. Research method

Starting from the theoretical foundations, the methodology of this article is presented as follows. The methodology of a case study is used and the rationale will be presented briefly (Cohen et al., 2007, pp. 253–263). The case study starts with the introduction of the degree course. Afterwards, the uniform design of the learning modules is outlined. As a next step, an empirical part is presented which includes a data collection and analysis followed by the discussion of results/findings. Although some quantitative data will be presented in this study, it opts for analytic understanding of the concept applied rather than statistical generalisation which is in line with the nature of this research method but also due to limited scope of this article. The idea is to show an example of good practice of a proven concept. In addition, the aim is to assist the IAMU community to apply the concept of visible learning by showing how to transfer it to similar cases in MET.

3.2. Degree course

The distance education degree course of International Maritime Management (IMM) is offered at the maritime faculty of Jade University of Applied Sciences (Jade UAS, n.d.) in Germany. IMM particularly addresses officers on merchant ships as well as professionals who work as (junior) maritime or logistics managers ashore. The design of IMM is characterised by a high level of flexibility which enables students to achieve their (second) university degree on master's level alongside work at a place of study of their choice – even on board the ship – and self-paced. Although the duration of study is flexible and students progress at their own speed, the typical duration of studies of the 90-credit points degree course is two and a half years of part-time study.

The educational design of IMM considers students' needs in consideration of organisational, content-related and didactic matters, and it is therefore based on a distance learning concept (see above). In line with the internationality of the maritime sector, the whole degree course is offered in the English language. The overall didactic approach of IMM emphasises the connection between academic theory and individual professional experience of the student group. On the one hand, the theoretical content provided by the lecturers should be applied to students' daily working routines and projects as well as professional environments. On the other hand, the proficiency and experience acquired in students' professional environments should be reflected on in a thoroughly academic manner. Theoretical analyses and examples of good practice go hand in hand. Students should further improve to take on personal responsibility, to exercise self-management, and to test out possibilities and implement their own ideas.

Learning modules start with study texts, which follow methodological-didactic concepts. Access to the material is possible 24 hours a day, seven days a week via the learning management system. Learners can also communicate asynchronously with their fellow students and lecturers anytime. Besides, lecturers provide detailed study plans which make structuring easier for students. In addition, they offer video conferences in the form of consultation hours. Participation is voluntary, but will support students' learning. Exams are also flexible in terms of time and location. Home assignments are supplemented by presentations offered as video conferences. Dates for submissions and presentations are announced well in advance so that module bookings can be coordinated with sea times and private appointments. Alternative dates are also offered upon request to meet both the requirements mentioned above as well as the attribute of flexibility.

In line with theoretical findings (see above), the degree courses' learning modules in the fields of maritime business and logistics, legal aspects, environmental management, process and project management, among other topics, are interconnected and the total of these learning outcomes lead to the education of maritime professionals. The objective is to educate maritime experts who operate ships with highly innovative technical systems, organise global transport chains, increase operational resilience but also increase the long-term appeal of maritime careers. Upon successful completion of the degree course, alumnae will possess key learnings in the aforementioned fields and should be able to apply all the following in the maritime and logistics context: ample and up-to-date knowledge, competencies which allow to manage projects, skills to interpret, assess and present results, key indicators and models, the capability to reflect on experience acquired, skills to organise own lifelong learning process as well as a comprehension of the demands and possibilities of intercultural relations, international co-operation and gender equality (Jade UAS, n.d.).

In the next sub-chapter, the focus will be on the concept of the IMM learning modules using the concept of Visible Learning (see above), namely the influencing contributor of 'self-reported grades'. On the other hand, we have to consider here that it is hardly possible to operationalise the 'collective teacher efficacy' or quantify the impact as its benefit or importance is rather a sense of identity and organisational challenge which, of course, all participating university staff involved is very aware of.

3.3. Learning modules

The design of the IMM learning modules builds on a uniform and learner-centred approach. Different didactic elements re-appear in all learning modules which will assist students to follow all learning modules more easily. Right from the start students gain access to all learning materials (study text, further readings and information as well as instructions for assessment). Students start by working their way through the information given which provides the theoretical framework. Self-instructional study texts are specially designed for distance learning students and play a key role here as there is almost no face-to-face contact. They feature the following didactic elements:

- At the beginning and at the end of all learning modules students fill in a questionnaire which contains statements referring to the module contents and intended learning outcomes. Learners self-assess their perceived level of knowledge, activate prior learning and see where they 'stand' within the learning module by means of a Likert scale which resembles the German university marking system: 1=very good knowledge, 5=no knowledge at all. Here, the scale was recoded and in the following higher numbers indicate higher marks. This approach follows the idea of Visible Learning and is very reliable (see above).

- The same idea re-appears in the study text as all chapters are prefaced with learning outcomes. Thereby, students are given an overview of the text that follows and so on.
- All chapters of the study text conclude with reflection questions which assist students to reflect on what they just have read, activate prior learning, link new knowledge with work experience or initiate forum discussions among the student group or with lecturers.

In parallel, students start the work on their examination by incorporating individual, work-related questions that are of personal interest. Alternatively, some modules include given examples or case studies. This approach facilitates a transfer between theory and practice with mutual benefits.

3.4. Data collection and analysis

In this paper, the subject of the data collection and analysis is the calculation of effect sizes which compares means from one group at different times. More precisely, a pre-post design measures the magnitude of change (efficiency) within a single group over time by calculating the standardised mean differences as Cohen's *d* (Cohen et al., 2007, pp. 520–525). In this case, the differences between a student group taken at two points of time are of interest. The values are collected with the initial and final questionnaires (self-assessments within the learning management system; see above) before and upon completion of the study of a learning module. For data protection reasons, the data were processed in anonymised form, which at the same time does not allow to conduct a repeated measures design. Moreover, in terms of evaluation, the final questionnaire contains some open-ended questions on overall learning satisfaction and improvement of the learning module in terms of positive as well as negative aspects.

In line with Hattie (2009, pp. 7–10) the effect size is calculated as:

$$d = (Mpost - Mpre) \,/\, SD \tag{1}$$

The study addresses results from the first learning module of the IMM degree course ('Academic Research Methods', ARM). Although this learning module does not seem to be the most maritime one in terms of content at first glance, it bears potential for an analysis in more detail especially for the following reasons. The first learning module of the degree course provides the basis and methodology for all university teaching and learning. In addition, in this context the ARM learning module serves as a very good example for illustrating the concept of work-integrated learning (see, for example, Jackson, 2015). The general idea of assessment in the IMM degree course focusses on the linking of theoretical frameworks with (maritime-logistics-related) practical projects of students' every day or working life (see above).

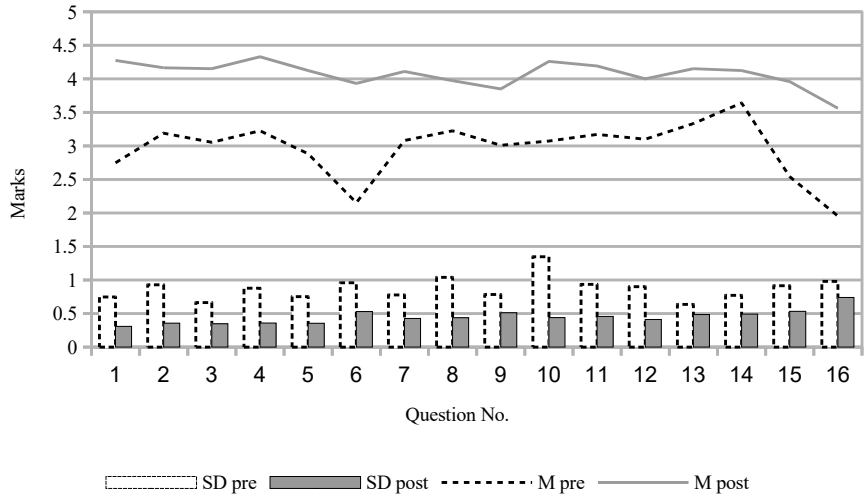


Figure 1. Students' perceived knowledge levels, own illustration following John et al., 2018, p. 120.

A successfully completion of a learning module goes along with learning gains. Here, completion refers to the comparison between the answers stated in the initial and final questionnaires which are calculated by the mean values of 16 statements/questions regarding the intended learning outcomes of the ARM learning module. Although the assumption in general is hardly surprising, we will calculate the actual effect, and thus provide

evidence and also compare it with the benchmark (see above). Furthermore, we find a minor number of outliers/exceptions in the material which we cannot analyse in more detail due to the limited scope.

The calculation shows that participants had a higher score after studying the learning module ($n = 73$, $M = 4.07$, $SD = .19$) than before ($n = 111$, $M = 2.96$, $SD = .43$). The calculated effect size ($d = 1.70$) is very large according to Cohen's guidelines (1992). The value is also higher than the effect size calculated by Hattie (2009; see above). The figure above shows all values of the two questionnaires.

Before the mean and standard deviation values presented in the figure above are analysed, some answers to the final open-ended question of the final questionnaire will be presented which also confirm students' perceived learning satisfaction. The final question is: "If there are any additional thoughts you would like to share with us, feel free to do so! We are happy to receive your feedback!" Some randomly selected answers are: "The module has helped me a lot to deal with academic research methods.", "No further specification." or "I like the structure of the course and also the content. It is a good mode to get started with the remote master's programme, because I think, these basics will be needed in all other courses, too."

3.5. Discussion of results/findings

During the most recent semesters, 111 students filled in the initial questionnaire prior studying the ARM learning module while 'only' 73 students also filled in the final questionnaire upon completion of the learning module. Although all students are asked to fill in the final questionnaire after having submitted their examination, this last step is not mandatory for technical and organisational reasons. The main reason for completion is that this step enables learners to estimate their perceived level of knowledge upon completion of the learning process and thus making their perceived learning progression visible. Moreover, data can, of course, be used for evaluation purposes and further improvement of the ARM learning module. In addition, results can contribute to further improvement of the IMM degree course but also initiate the transfer to other MET programmes. Based on the data, completion and non-completion rates of approximately 80 (20) per cent result which can be considered positive for a distance degree course (see, for example, Bawa, 2016; Lee and Choi, 2010). This finding suggests that visible learning might be a factor that positively influences student retention in distance learning courses. However, the numbers are relatively low and therefore further investigation is required.

The figure above shows students' perceived knowledge levels as mean values (average value of a dataset) and standard deviation (dispersion or spread of the data points around that mean). Basis of the calculation are 16 statements/questions regarding the intended learning outcomes of the ARM learning module. The figure also shows that all values increase which in the first place means a higher level of perceived knowledge in all areas upon completion of the learning module; this refers to the mean values. However, this finding is not very surprising. In addition, the figure also shows that participation in the learning module leads to a higher level of homogeneity across all participants; this refers to the standard deviation. Furthermore, both the magnitude of change as well as the initial and final levels vary across the different theme categories which should be further analysed; this is out of this paper's scope.

The results, namely the data analysis but also the answers to the open-ended questions illustrate the importance of the constructive alignment within the learning modules from learning outcomes to contents and examination. In line with the research findings discussed above (see chapter 2), a learning environment where no immediate feedback can be given to students (at sea), a transparent and visible learning progress is indispensable for maintaining student motivation and retention. Results indicate the relevance of visible learning, student support and the importance to guide participants through their distance learning studies (at sea), for example, by giving orientation in terms of expectations and assessment but also in terms of time estimates as well as by designing module content in manageable steps.

In general, but on a more implicit level the results show that IMM students in the context of LLL also improve their level of self-organisation and personal competencies respectively. As part-time studies alongside work challenge students in several ways, they progress in terms of self-management by achieving further indirect learning objectives, such as the improvement of language skills, intercultural competencies, more structured methodological approaches due to a more professional working habit, among other things. Such learning outcomes make them better in the workplace (work more structured and concise), enable them to adapt to new challenges, tasks and projects, and more generally speaking strengthen them in terms of the organisation

of their own LLL. In addition, (further) education helps to increase operational resilience and the long-term appeal of maritime careers. It also supports to preserve a sustainable workforce and well-being which at the same time contributes to maintain or at least accomplish safe, fair, inclusive and attractive working conditions.

4. Summary, conclusion and outlook

The article analyses the importance of visible learning (Hattie, 2009) in MET. The study uses the example of a case study. The International Maritime Management, MSc distance degree course enables seafarers to achieve their master's degree in part-time mode of study alongside work. This gives officers the opportunity to become lifelong learners by using the time they spend at sea for further education. This entails unique requirements as seagoing ships as places of learning are particularly difficult to access due to its specific characteristics (students are at sea for several months and they are located in different and changing time-zones with limited Internet access). Therefore, the article provides information about the degree course's didactic concept including its learning modules which is aligned along those needs and some empirical data including its analysis. Information is used in order to further strengthen MET as well as attractive working conditions, educate a sustaining workforce, promote gender equality but also enhance the appeal of maritime careers.

The workforce needs the ability to adapt to change, new situations and technology. In line with these demands, distance learning approaches seem to be promising and most appropriate although such learning puts high demands on students' self-competence in terms of balancing responsibilities of family or work into their learning efforts. Therefore, it is of utmost importance to consider visible learning (especially 'self-reported grades'), promote academic support, enable a self-paced mode of study where material is always available and students' progress at their own speed with the aim of providing a maximum of ease for students in terms of the framework conditions; provide an environment that they are not studying the contents alone. In addition, student feedback and cooperation among the teacher group ('collective teacher efficacy') constitute triggers for change and adaptability. These sources of information should directly be converted into further development of MET concepts across different levels.

In terms of limitations and future work, further evaluation seems to be reasonable in terms of a more detailed and thus reliable statistical data analysis regarding the ARM learning module, for example, with the aim of a more extensive data collection and analysis as well as hypotheses testing. Further analyses may also refer to further learning modules of the IMM degree course but especially to degree programmes offered at other IAMU member universities. Thus, a comparison becomes possible. Evaluation results may also refer to the transfer of findings to other degree courses in the IAMU community. Thereby, the paper promotes the topic of "Human-centered digital oceans: Educating safe & green global maritime professionals" and strengthens the roles of (distance) learning and LLL in MET. The study also reveals further need for research regarding the impact of visible learning on completion rates in distance learning.

Details and possible solutions to the research question raised were presented. In summary, the findings of this paper underline the importance of the concept of visible learning in MET. This was illustrated by using an example of good practice. The study constitutes a platform for cooperation and dissemination which allows IAMU members to benefit from each other. Moreover, it opens up opportunities for cooperation and comparative studies across the IAMU community and gives a clear path forward.

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A Needs-Based Upgrade of Maritime English Syllabus: Integrating Human-Related Issues

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Abstract: As technological innovation is rapidly introduced to support a sustainable maritime industry, enhance maritime safety, and protect the marine environment, the human element remains the key factor that determines whether the industry performs efficiently. Being a complex multidimensional issue, the human element needs to permeate the entire realm of seafarers' training, as this necessitates a deeper understanding of the required skills, proficiency, knowledge, and traits that maritime professionals need to possess. The potential for envisaging those tendencies in tandem with industry partners and then incorporating the devised content into thoroughly tailored syllabi might be found at maritime education institutions.

The Maritime English course has miscellaneous opportunities for students to gradually immerse themselves in understanding the human element and the leaders' role in decision-making, organizing teamwork, threat and error management. It also promotes the development of essential human skills, such as kind leadership, critical thinking, decision-making, risk assessment, among others. Another advantage is the possibility to upgrade the syllabus relatively quickly in response to dynamic changes occurring in operational practice. Building on these opportunities, the authors have designed and implemented the Maritime English syllabus that primarily focuses on mastery of communication skills through embedding human skills development.

Keywords: Maritime English; syllabus upgrade; human-related issues; future seafarers' training

1. Introduction

The shipping industry has been well regulated by both national and international laws, while the potentially interested parties significantly influence maritime standards and make a demand on MET institutions for competent, well-trained seafarers. Being aware that the wide introduction of digital technologies, as well as the automation of basic working processes, has created new opportunities for the industry, highlighting the essential necessity to revise the seafarers' professional competencies.

Recent studies on current trends indicate the need to develop professional competencies and human skills to ensure the sustainable development of the industry (Pazaver and Kitada, 2025). Stakeholders, including shipping companies, regulatory bodies, insurers, and the global maritime community, are increasingly recognizing the influence of the human element on the efficiency of onboard processes and call for improvements in maritime education.

The safety of the ship, her cargo, and environmental protection have dramatically depended on a human's ability to analyze information, evaluate risks, make quick and right decisions, build action plans, and communicate it to the other people involved. The focus on the human element training has a significant potential to contribute to the future leaders' formation, and, ultimately, to ensure the safety of life at sea, maritime security, and work efficiency (IAMU GMP, 2019). Thus, there is an objective inquiry to substantiate the importance of human skills for an individual's successful career and describe practical approaches to integrating human-related issues into the educational process. At present, alongside the focus on cutting-edge technologies, the skills that emphasize human-to-human interaction are gaining the attention they deserve.

We understand human-related issues, the way many researchers do, as social, psychological, and cultural factors that influence individuals, teams, and organizations. They represent the human dimension of problems, such as communication breakdowns, conflicts, and personal, emotional, or physical challenges. This leads to the need for profound awareness of the skills that future seafarers should acquire. Soft skills, which the authors consider synonymous with human-related skills and therefore use interchangeably throughout this paper, are behavioural, emotional, and cognitive traits, apart from abilities to perform job duties, which shape professionals to foster a productive working environment (Kudryavtseva et al., 2024).

2. Literature Review

Many theoretical considerations and researches regarding the importance of human skills for today's workforce have been presented to the wider public.

A collective of researchers from the World Maritime University confirms the importance of soft skills in enhancing technical skills and highlights the underestimation of the human factor in maritime education. To that, they underscore the need to amend the STCW Convention and suggest a list of skills required for seafarers in the short, medium and long terms, including: 1) human resources management; 2) business communication; 3) quality and safety control; 4) critical thinking and analysis; 5) application of digital technologies; 6) stress resistance and flexibility; 7) leadership and initiative; 8) active learning; 9) personal abilities (Ölçer et al., 2023). The list above covers the most essential aspects of seafarers' professional activities, with further detailing of their content.

The SkillSea project (2023) recommends introducing a number of separate courses for the development of soft skills in maritime education, namely: 1) digital technologies; 2) environmentally mature behaviour; 3) leadership, communication, and teamwork; 4) conflict management. The project is a further attempt to specify the skills vital in the contemporary maritime industry.

The Kind Leadership project, implemented under the auspices of the UK Maritime Professional Council, proposes adding "Human Element, Leadership and Management" course to the curriculum with the aim of encouraging students to develop their leadership skills necessary to create a positive working environment (Davis et al., 2022).

A particularly relevant European initiative is the Erasmus+ project iSOL-MET, "Innovative Soft Skills to Maritime Education and Training" (2023), which addressed the gap between shipping industry expectations and soft skills development in maritime education. The project developed case-study-based educational materials to connect students' limited operational experience with real-life onboard and shore-based maritime practice. Its deliverables, including a Maritime Case Study Handbook, guidelines for soft skills materials, and evaluation tools, are particularly suited to Maritime English, as case-based learning inevitably involves students reading, interpreting, discussing, negotiating, justifying decisions, and reflecting on alternative courses of action.

Already in Resolution A.850(20), the International Maritime Organization (IMO) (1997) defined the human element as a complex multidimensional issue that affects maritime safety and marine environmental protection and should be addressed effectively. Nonetheless, the adopted eighteen years later Model Course 3.17 "Maritime English" (2015) does not mention it covering technical topics and ways of teaching the language exclusively. The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW), mandates technical standards (IMO, 2017), although in its latest amendment, a mandatory module on the prevention of bullying and harassment was included to address the psychological impact of hostile work environments on shipboard safety (IMO, 2024).

With numerous codes, resolutions, shipping company guides, projects, and approaches, though, the string of incidents and accidents at sea due to human errors continues to be fueled. The predominant emphasis on technical aspects at maritime educational institutions might be among the possible root causes leading to such state of things.

Considering that human skills are implicitly touched upon in numerous studies and projects, their integration into Maritime English course appears to be an effective approach to enhance interpersonal communication on board (Chirea-Ungureanu, 2025). However, publications on how these skills may be acquired by students within Maritime English course are quite rare. A detailed analysis of methods for soft skills development, with an emphasis on communication, reveals that task-based and problem-solving learning,

case studies, role-plays, discussions, debates, oral and poster presentations, and written tasks related to future professional activities are the most appropriate methods for incorporating soft skills into the English classes (Sirbu and Georgescu, 2023).

The paper is aimed at presenting human-related skills as an inherent element of the Maritime English course for maritime students at education institutions and proposing an upgraded Maritime English syllabus that integrates selected soft skills and content tasks within specific thematic modules. Additionally, the authors share their expertise and provide practical insights into enhancing professional communication effectiveness by addressing human element issues.

3. Survey Analysis

This study uses a survey to investigate current practices for embedding human-related issues into a language course and to gain professional insights on prioritizing teaching and learning approaches**.** The inquiry has been addressed to maritime educators engaged in the development of language courses from several European universities, namely Constanta Maritime University (Romania), Maritime University of Szczecin (Poland), the Department of Shipping, Trade and Transport, University of the Aegean (Greece), and Kherson State Maritime Academy (Ukraine). The survey, designed in Google Forms, consists of five open-ended questions. The survey link has been shared with 11 participants to gather their perspectives on how integrating human-related skills would enhance the Maritime English course.

The first question aims to identify which human-related skills are essential for seafarers' onboard effective performance. Figure 1 shows the participants have prioritized communication skills as vital to enhancing safe working practices. In addition to the ability of interacting in English, the need to coexist and collaborate effectively in a multinational environment has been widely recognized as a key skill for seafarers.

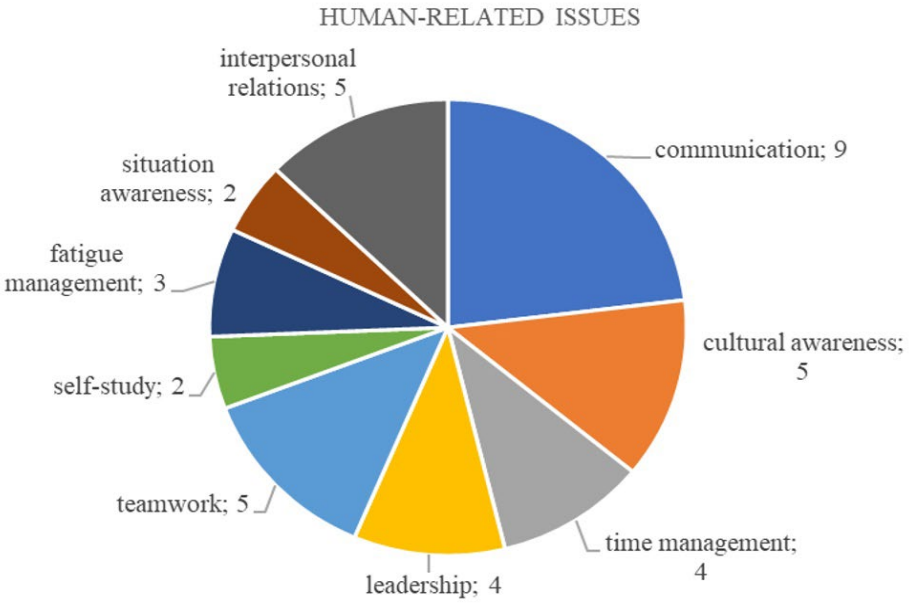


Figure 1. Survey findings (by number of respondents).

Figure 1 also illustrates the significant roles of teamwork and leadership, grounded in interpersonal skills such as ambition, self-discipline, trustworthiness, and empathy, as well as professional skills in the maritime domain. To meet industry standards, increase merchant efficiency, and ensure the safety of the marine environment, respondents have highlighted the need to train in effective time management, stress resistance, and fatigue reduction at sea. Chronic stress negatively impacts seafarers' ability to analyze large volumes of data from various sources, perceive and evaluate critical factors, and make sound decisions with proper situational awareness. Last, but not least, lifelong learning skills must be well developed to succeed in a career path and to support the well-being of seagoing specialists.

The second question seeks experts' judgment on the potential of the Maritime English course to contribute to the human-related skills development. The answers collected show that the respondents have been unanimous in their view of the language course perspective, given its initial focus on the acquisition of communicative competence and on fostering critical thinking. The respondents' current teaching practice demonstrates that the Maritime English course can play a critical role in reducing miscommunication and promoting effective collaboration and leadership in multicultural teams. As an integrative discipline, the Maritime English course serves as a tool for unifying professional knowledge from several disciplinary areas, including ship conning, computer science, environmental sciences, and cargo transportation, with special emphasis on interpersonal relations.

The third question investigates current practices across different maritime institutions for integrating human-related issues into language course syllabi. The analysis reveals that, because curricula differ across education providers, just a few institutions integrate these issues into their Maritime English courses. Almost everyone among the respondents emphasized the role of valiant instructors and their individual efforts, rather than institutions, in encompassing core competencies alongside broader human factor issues. Analyzing the suggested answers could identify applicable methods to enhance this integration. Firstly, the Maritime English syllabus could include topics focused on a person's behaviour, in addition to profession-oriented content, and boost learners' interaction. The use of authentic materials, such as various nautical publications, could expose students to professional-oriented tasks, thus increasing their motivation to communicate and to share core knowledge and seagoing experience of onboard processes and procedures. All respondents emphasized the importance of choosing appropriate teaching approaches; among the most effective ones were mentioned case studies, role-plays, and scenario-based tasks. Such learning activities provide opportunities to apply knowledge, compare different practices, evaluate various options, and create new scenarios. These tasks stimulate active learning, foster personal interactions, and, as being of utmost importance for our study, implicitly address various human-related issues.

The fourth question explores the challenges that Maritime English teachers face when embedding human-related issues into the existing course. Most respondents, regardless of the universities they represent, have highlighted the same typical obstacles that are likely to hinder the success of such language courses. As language specialists, the majority of Maritime English teachers lack seafaring experience and do not have a clear vision of interacting in a multicultural environment under a strong hierarchical structure on board. While human-related issues are often closer to team management, leadership, or safety management courses, Maritime English teachers would have to move beyond the language itself into the operational judgment and shipboard behaviour. Among the questions that language teachers still struggle to resolve, the main one is what criteria to use to measure learners' progress, as well as the appropriate balance between language knowledge, professional communicative competence, and behavioural skills. Another challenge concerns the limited learning resources and the need to determine which human-related issues are typically associated with a given communicative scenario.

The last question seeks possible solutions and measures to strengthen the integration of human-related issues into the Maritime English syllabus. Most respondents highlight the need for institutional support to adapt syllabi to the actual needs of the maritime field. Firstly, to seek seagoing expertise, short teacher training courses on human-related topics could be offered to help teachers avoid designing pseudoscientific curricula, and enhancing interdisciplinary collaboration between faculties and experts in maritime subjects would improve situational awareness. Secondly, adequate teaching materials based on authentic resources should be designed to address existing gaps and foster a deeper understanding of the actual problems of human interaction on board. Thirdly, task-based learning grounded in real onboard scenarios needs to be systematically incorporated into the classes to create an active learning environment.

The survey analysis was aimed at exploring trends in integrating human-related skills into the educational process across several maritime institutions in Europe. The findings have clearly revealed the teaching staff's awareness of the skills value for the industry's sustainability and their deep concern about the necessity to update the existing academic courses. Nevertheless, the analysis identifies growing concerns about the state of affairs when the course syllabi redesign is initiated by enthusiastic educators rather than by the institutions.

Along with the human-related issues listed, communicative competence has been recognized as being of primary importance; therefore, the Maritime English course, which focuses on developing professional

communication skills, is among the most promising, as it offers multiple opportunities to organize discussions and debates.

The probing into possible ways to integrate human-related skills, as suggested by the respondents, would help embed human behaviour-related topics, design authentic learning materials, and choose appropriate teaching techniques to empower such skills training. Among the questions that emerged, the criteria for assessing skills development require wider discussion in the pedagogical environment.

4. Syllabus Configuration

In the proposed Maritime English syllabus undergraduate students improve their communication skills and get proficient in miscellaneous aspects of safe onboard work: cargo handling, security procedures, risk assessment, and more. It consists of six modules where the lesson topics tend largely to depicting and discussing technical aspects of the operational processes.

Our belief is that the targeted course design based on newly-sprung industry needs should embrace technical topics with human-related issues as technical knowledge and skills by themselves cannot be regarded as sufficient for career success anymore. Safety of crews and ships can be honed by sharpening the focus on the behavioural patterns, as well as on their cognitive triggers.

Certain inconsistency among researchers exists in their attempts to define human-related issues discordantly: non-technical skills, human element, soft skills, human factors, behavioural patterns, attaching variable meanings to them. It cannot be denied that those issues cover all human factors affecting maritime safety and performance – such as leadership, communication, problem solving, decision-making, teamwork, emotional intelligence, critical thinking, situational awareness, and crew well-being.

A close investigation of the soft skills, imperatively required for the seafarers-to-be, brought us to compiling a list of non-technical abilities and aligning them with the modules to be mastered by the students (Table 1). The survey findings and the authors' teaching experience were taken into consideration to target appropriate human-related skill development in each learning module. The order of modules was prompted by the sequential stages: first, general work with the crew – crew resource management, security procedures; then direct operational procedures – risk assessment, arrival procedure, and cargo handling; finally, after-effects steps – shipboard inspections and surveys. Deeper learning of soft skills begins with the foundational skills and gradually moves to more complex skills like leadership and decision-making.

Table 1. Modules and relevant soft skills aligned.

Modules		Soft Skills
Crew Resource Management	⟶	Teamwork
Security Procedures	⟶	Emotional Intelligence
Risk Assessment	⟶	Critical Thinking
Arrival Procedure	⟶	Decision-Making
Cargo Handling	⟶	Situational Awareness
Shipboard Inspections	⟶	Leadership

In the upgraded syllabus (Table 2), the lessons are planned with dual objectives – communicative (referring to onboard operations) and analytical (referring to soft skills). Supposedly, each module concentrates on one soft skill to be 1) understood and applied; 2) analysed; 3) reflected upon by students. Transitioning from one module to another, students gain the opportunity to systematically analyze an increasing number of soft skills.

At the level of understanding and applying, the students are to explain certain ideas or concepts by classifying, summarizing, inferring, and using information in new situations. A list of activities for understanding may include gap-fill, question-answer, true-false statements, odd cells, reading and speaking, and audio recordings of conversations, from which students get to know the possible ways of demonstrating specific soft skills and can share their opinions and real-life experience.

Table 2. Modules and relevant objectives aligned.

Module	Communicative Competence	Analytical Competence
	The students will be able to	
1. Crew Resource Management	speak about effective crew interactions in performing operational tasks	understand how teamwork improves productive collaboration and enhances success in the workplace
2. Security Procedures	describe duties of ship officers in relation to the ISPS Code	recognize emotional triggers and their impact on connecting with others
3. Risk Assessment	describe the procedure and basic principles of risk assessment	characterize ways of assessing situations rationally and objectively
4. Arrival Procedure	characterize port services and pre-arrival documentation	distinguish between reactive and proactive decisions to analyse the available information
5. Cargo Handling	demonstrate knowledge of IMO regulations on proper transportation of cargoes by sea	explain the process of identifying potential hazards and responding to unpredictable incidents
6. Shipboard Inspections and Surveys	describe the procedures of shipboard inspections / surveys and their requirements	evaluate some expectations and evidence-driven decisions by ship officers

The level of analysis requires drawing connections among ideas by differentiating, structuring, and contrasting. Possible activities for analysis presuppose half-page stories for character study, sea stories, cases, maritime accident reports (MARs), simulations, role-plays, gamified scenarios, debates, Q&A meetings with experienced seafarers, pairs/mini-groups in break rooms to share success stories, discuss what made it successful, and identify common themes. Learning common cognitive patterns giving rise to failures is also of profound significance for future seafarers due to the possibility of structured self-reflection. With this purpose in mind, cases, MARs and other descriptive sources of problematic behaviours and non-expected outcomes need to be supplemented by adding the context concerning psychological triggers and behavioural patterns.

Reflection moves learners beyond routine memorization into higher-order thinking, enabling them to evaluate their or somebody's actions, analyse strengths/weaknesses, and create new understanding based on experience. It acts as a bridge, transforming conceptual knowledge into critical thinking and self-directed learning. Reflection is deeply rooted in evaluation. Students make judgments, criticize or appreciate the effectiveness of behavioural strategies. Activities for reflection: reflective journaling, discussions, goal-setting reviews, self-reflection, and writing reports. Communicative activities, concentrated on reflection upon their personal and someone else's experience, promote self-awareness and critical thinking, encouraging students to plan for future growth.

All of the above leads us not only to a deeper understanding of the situations being analysed, but alongside to the necessity of evaluating the students' analytical skills reliably. To assess theoretical knowledge of the soft skills impact, habitual activities like multiple option choice, completing sentences, or highlighting certain phrases in a text may be used for quantitative assessment. Needless to point out that assessing their perceptions, reactions, and self-analysis should be qualitative. To be positively involved in the process of soft skills analysis, students do not need additional assessment points, but should be negotiated with, instead. Possible tools for qualitative tracking of the undergraduates' takeaways comprise simulation of realistic scenarios, role-plays, structured interviews, and regular questionnaires.

5. Conclusion

In response to the current needs of the shipping industry, human-related issues and soft skills content should become an integral part of study programmes at maritime education institutions whether those may be obligatory or optional syllabi. The present paper indicates that the Maritime English course appears to be an advantageous ground for fostering this innovation. It can provide a practical and flexible environment for embedding these skills by naturally involving interaction, negotiation of meaning, decision-making, feedback, and reflection.

The survey findings reveal the educators' mindful positivity toward inevitable challenges, which boosts confidence in their ability to rigorously implement this subject matter. Furthermore, the Maritime English teachers have demonstrated knowledge in organizing a variety of communicative activities.

Discussions on miscellaneous topics, case studies, analysis of texts and videos, Q&A sessions with experienced seafarers, and more, aided by undergraduates' self-reflection, are a promising set of tools for achieving the expected learning outcomes. As a result, the proposed Maritime English syllabus can be strengthened by implementing a series of case studies, small-group analyses, class discussions, debriefings, and reflective follow-ups. It would help transform Maritime English from a mainly language-oriented course into a structured environment for practicing the human element of safe and efficient shipboard performance.

The researchers' future endeavours concern designing a set of workshops on methodology of developing soft skills, as well as a bank of dedicated study materials.

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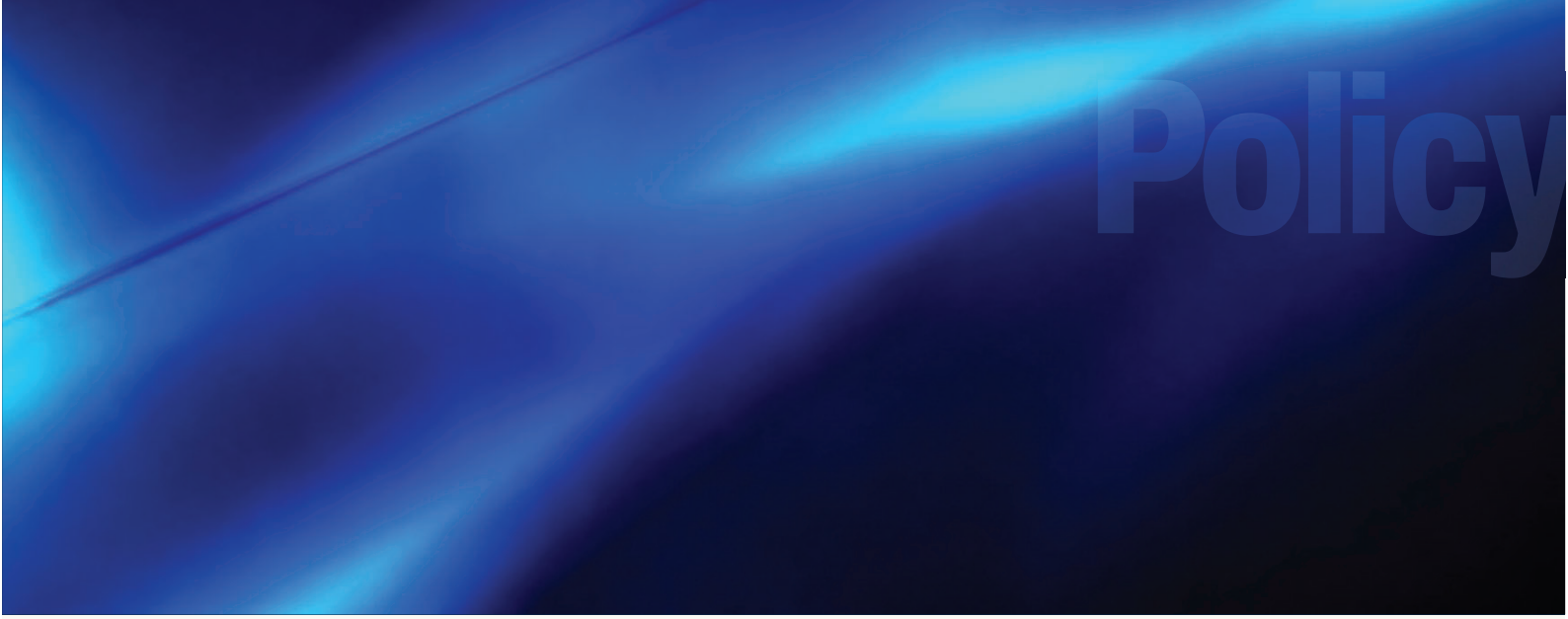
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Designing an Industry Advisory Board for Global Maritime Education: An Action Research–Based Organizational Development Model for the IAMU

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Abstract: The International Association of Maritime Universities (IAMU), as a global network of maritime higher education institutions, is expected to maintain close and effective relationships with the maritime industry to ensure that education, training, and research remain aligned with technological, environmental, and workforce demands. In line with the IAMU Tokyo Statement, this study presents an action research–informed organizational development (OD) initiative to design, establish, and evaluate an Industry Advisory Board (IAB) as a structured mechanism for sustained industry engagement.

The project adopts a cyclical action research framework consisting of four phases: appraisal, planning, execution, and monitoring. The appraisal phase critically examines the IAMU's current organizational structure, existing practices, and expectations concerning industry collaboration through document review and stakeholder consultation. The planning phase focuses on co-designing the IAB, defining its mandate, membership profile, governance structure, and operational procedures through iterative engagement with the IAMU leadership and stakeholders. The proposed execution phase involves piloting the IAB, while the monitoring phase introduces a systematic evaluation approach utilizing qualitative inquiry and performance indicators to assess perceived value, operational effectiveness, and areas requiring improvement.

By integrating organizational development theory with action research and stakeholder-based governance, this study offers a transferable model for embedding industry advisory mechanisms within international higher education associations. The findings are expected to support the IAMU's long-term institutional capacity building and contribute to the development of more responsive, human-centered, and future-oriented maritime education systems.

Keywords: Industry Advisory Board (IAB), Organizational Development, Maritime Education and Training (MET), University–Industry Collaboration

1. Introduction

The International Association of Maritime Universities (IAMU) was established in 1999 as a global network of maritime higher education institutions committed to advancing maritime education, training, and research. With a membership exceeding eighty universities and academies across all continents, the IAMU occupies a distinctive position at the intersection of academic excellence and international maritime governance, a position made explicit in the Tokyo Statement of 2019, which mandates the IAMU to originate and maintain close relationships with the global shipping industry and relevant stakeholders (IAMU, 2019).

Decarbonization imperatives, autonomous and remotely operated vessels, the digitalization of shipboard and port operations, and evolving IMO regulatory frameworks are collectively reshaping the competency requirements for maritime professionals. Caesar (2024) confirms that the pace of this transformation outstrips the capacity of maritime education and training (MET) institutions to respond in real time, a gap attributed in significant part to the absence of structured industry feedback mechanisms within academic governance (Rybnicek and Königsgruber, 2019).

Despite the IAMU's engagement with the sector through its Liaison Committee, IMO participation, and member university partnerships, the appraisal phase of the BRIDGE-IAB Project identified a structural gap:

no institutionalized advisory mechanism existed within the IAMU's governance architecture to channel systematic industry input into strategic and educational decisions. Industry interaction, where it occurred, was event-based, relationship-driven, and decentralized — qualities Genheimer and Shehab (2009) identify as characteristic of advisory structures that fall short of their institutional potential.

This paper presents the methodology, governance design, and outcomes of the BRIDGE-IAB Project, an action research–informed organizational development (OD) initiative funded by The Nippon Foundation under the IAMU's FY2025 Organizational Development Project scheme. The project was implemented jointly by Maine Maritime Academy (USA) and the Maritime Faculty of Istanbul Technical University (Türkiye). Its central objective was to design and develop a roadmap for an Industry Advisory Board (IAB) as a governance-compatible, institutionalized mechanism for sustained industry engagement within the IAMU.

2. Literature Review

2.1. Industry Advisory Boards in Higher Education

Voluntary advisory boards of industry practitioners are near-universal in technical and engineering education, though research on their effectiveness remains limited. Genheimer and Shehab (2009) proposed a four-dimensional effectiveness model built on human relations, internal processes, rational goal attainment, and open-systems interaction, validated through surveys of ninety engineering school directors and board members. Effective boards, they found, share three characteristics: a clear advisory-only mandate, formal operating procedures, and meaningful integration with institutional leadership.

Davis (2006), Summers (2002) and McIntyre and Fox (2014) reached complementary conclusions: high-impact boards require explicit goal-setting, diverse membership, and predictable meeting structures with defined follow-up. Calitz et al. (2019) extended this to international and multi-stakeholder configurations, showing the conditions for IAB effectiveness are broadly consistent across institutional contexts.

2.2. University–Industry Collaboration: Governance and Sustainability

Rybnicek and Königsgruber (2019), in a systematic review of over fifty empirical studies on university–industry collaboration, identified governance design as the strongest predictor of partnership sustainability. Successful collaborations feature clearly defined roles, mutual benefit, and mechanisms for managing organizational-culture differences — all addressed in the BRIDGE-IAB governance design. Awasthy et al. (2020) distinguish transactional (project-based, time-limited) from relational (continuous, institutionally embedded) engagement. BRIDGE-IAB targets relational engagement by embedding the advisory mechanism within the IAMU's existing governance structure, consistent with the finding that sustainability depends on institutional integration (Lucietto et al., 2021).

The Triple Helix model of university–industry–government relations (Etzkowitz and Leydesdorff, 1998) provides a complementary theoretical lens. The IAMU sits at the convergence of all three pillars: as an academic association, as an organization holding IMO consultative status, and as a strategic partner of the global shipping industry. The IAB is designed to formalize and institutionalize the industry strand of this relationship.

2.3. Action Research as Organizational Development Methodology

Action research is well established in organizational development as a method combining inquiry with intervention through iterative, participatory cycles (Reason and Bradbury, 2001). Its cyclical structure — appraisal, planning, action, and reflection — allows practitioners and researchers to co-produce knowledge while addressing real organizational problems. The Action Research Engagement (ARE) framework indicates that stakeholder communication and active sponsor involvement across all phases are the strongest determinants of successful governance change projects. This finding directly informed the BRIDGE-IAB design: the project team ensured regular engagement with the IAMU leadership and the Secretariat throughout the intervention.

2.4. Stakeholder Theory and NGO-to-NGO Collaboration

The decision to engage international NGOs rather than individual shipping companies draws on two bodies of literature. First, the stakeholder salience model of Mitchell, Agle and Wood (1997) provided the

framework for mapping maritime NGOs by power, legitimacy, and urgency, replacing ad hoc, relationship-based selection with a systematic, evidence-based methodology. Second, the NGO-to-NGO partnership literature confirms that collaborations between organizations sharing related objectives but complementary expertise tend to exhibit higher levels of mission alignment, reduced conflict of interest, and greater representational legitimacy than corporate–academic partnerships. These qualities are essential for an advisory mechanism operating within an international academic association whose governance must remain independent of commercial interests.

3. Methodology

The Project adopted a four-phase action research–informed cyclical methodology (Figure 1), with findings from each phase informing subsequent design decisions. The project is at the design-and-validation stage: appraisal and planning are complete, execution is partially complete (institutional presentation and external consultations conducted), and monitoring is prospective, defining the evaluation framework to be applied once the IAB is operationalized. This paper therefore reports a validated governance design and implementation roadmap rather than the outcomes of a fully implemented intervention.

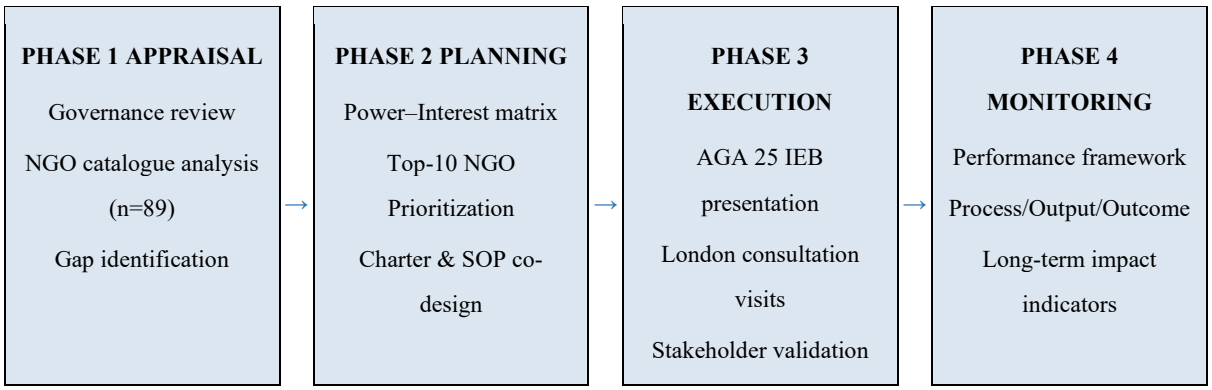


Figure 1. Four-Phase Action Research Methodology of the BRIDGE-IAB Project.

3.1. Appraisal Phase

The Appraisal phase examined whether an IAB was institutionally appropriate for the IAMU, what models existed in the literature, and what structural gaps characterized the IAMU's current engagement framework. Review of the IAMU's governance documents — the Basic Agreement, the Tokyo Statement, and Liaison Committee records — confirmed a clear mandate for industry engagement but revealed no dedicated advisory structure.

All 89 international NGOs holding IMO consultative status were then reviewed, analyzed by mandate, geographical reach, and sectoral coverage, and classified as Operational, Advocacy, or Hybrid NGOs. This classification formed the basis for Phase 2 prioritization. Classification was applied by the project team on the basis of each organization's stated mandate, operational scope, and sectoral focus, drawn from the official IMO list of NGOs in consultative status. Operational NGOs were those engaged in implementation, technical standards, and sector coordination; Advocacy NGOs those focused on policy influence; and Hybrid NGOs those combining both functions.

3.2 Planning Phase

The Planning phase applied a Power–Interest matrix to all 89 IMO-accredited NGOs, evaluating each on (a) influence over MET policy and practice and (b) mission alignment with the IAMU's objectives, identifying ten priority candidates. Table 1 summarizes the gap analysis that shaped the IAB's design mandate. Each NGO was scored on two five-point scales (1 = lowest, 5 = highest): power, defined as influence within the maritime industry and its regulatory platforms; and interest, defined as mission relevance to the IAMU and to MET. Scoring was conducted jointly by the project team and reviewed in a dedicated deliberation meeting. Organizations in the high-power/high-interest quadrant were prioritized, narrowing the

pool of 89 NGOs to a shortlist of ten. Table 2 presents the NGO classification framework and the selection criteria applied in the Power–Interest analysis.

Table 1. Organizational Gap Analysis: Current Situation and Proposed IAB Contribution.

Current Situation	Challenge Identified	Proposed IAB Contribution
Industry interaction occurs through informal, event-based contacts	No systematic, continuous dialogue with global maritime NGOs	Structured, recurring consultation platform within IAMU governance
No formal NGO-to-IAMU feedback mechanism	Fragmented and decentralized industry engagement	Coordinated advisory mechanism with defined reporting lines
Curriculum and research alignment depend on individual institutions	Weak feedback loops between MET and industry expectations	Regular industry input to IAMU strategic and educational discussions
IAMU holds global standing but lacks operational NGO engagement	Missed strategic collaboration opportunities	Formal, governance-compatible interface with priority NGOs

Table 2. NGO Classification Framework and Selection Criteria.

NGO Category	Primary Function	Selection Criteria Applied
Operational	Implementation, industry coordination, service provision	IMO consultative status; international membership scope; MET-relevant mandate; mission compatibility with the IAMU
Advocacy	Policy influence and sector-wide awareness	Same criteria as above
Hybrid	Combined operational and advocacy functions	Same criteria as above; higher weighting for Power–Interest matrix score

Four governance documents were produced: a draft IAB Charter defining institutional positioning, membership, roles, and reporting lines; a Standard Operating Procedures (SOP) handbook; a Web Content Framework; and a mission alignment matrix demonstrating strategic fit with all five IAMU mission items (Table 3).

Table 3. The IAMU Mission and IAB Goals Alignment Matrix (X = High Alignment).

IAMU Mission Item	Enhanced Collaboration	Industry Relevance	Curriculum Guidance	Stakeholder Engagement	Research Collaboration	Strategic Insights	Periodic BoK Review
A. Create and maintain a global network for maritime human capacity building		**X**		**X**	**X**	**X**	
B. Advance Global MET through scientific and practical approaches	**X**	**X**	**X**	**X**	**X**	**X**	**X**
C. Develop effective MET for future maritime professionals (safety, security, environment)			**X**				**X**

D. Disseminate research results to interested parties	**X**	**X**		**X**	**X**		
E. Communicate with IMO and the maritime industry on Human Element and MET	**X**			**X**			**X**

**BoK = Global Maritime Professional Body of Knowledge*

A defining feature is the IAB's strict advisory-only status: it holds no decision-making authority, which remains entirely with the International Executive Board.

3.3 Execution Phase

Execution involved two forms of stakeholder engagement. First, the model was presented to the IAMU International Executive Board (IEB) at the 25th Annual General Assembly. Feedback focused on governance terminology, advisory positioning, and sequencing; the IEB recommended a time-bound working group before full institutionalization, which was incorporated into the roadmap. Second, consultation visits were held in London on 3–4 November 2025 with the Institute of Chartered Shipbrokers, the International Chamber of Shipping, and the International Maritime Organization. Each consultation followed a common presentation of the proposed advisory model; discussion notes were recorded, reviewed jointly, and used to refine governance terminology, reporting structure, and Secretariat linkage. Discussions examined governance compatibility, advisory role, and institutional relevance. Across all consultations, the advisory-only, non-binding character of the mechanism was well received.

3.4 Monitoring Phase

The Monitoring phase established a performance evaluation framework, structured around four indicator levels, to assess IAB effectiveness once operationalized (Table 4).

Table 4. Performance Evaluation Framework for the IAMU-IAB**.**

Indicator Level	Indicator Examples	Data Sources
Process	Meeting frequency; participation rates; documentation quality; notice compliance	Meeting minutes; attendance records; SOP audit
Output	Number of advisory recommendations issued; LC-reported advisory contributions; web content updates	Annual IAB report; LC reports to IEB
Outcome	Perceived relevance to the IAMU strategic decisions; MET curriculum alignment feedback; member satisfaction	Post-meeting surveys; structured interviews with IEB members
Long-term Impact	Member university capacity development; Body of Knowledge review contributions; NGO partner retention rates	Multi-year evaluation reports; AGA review sessions

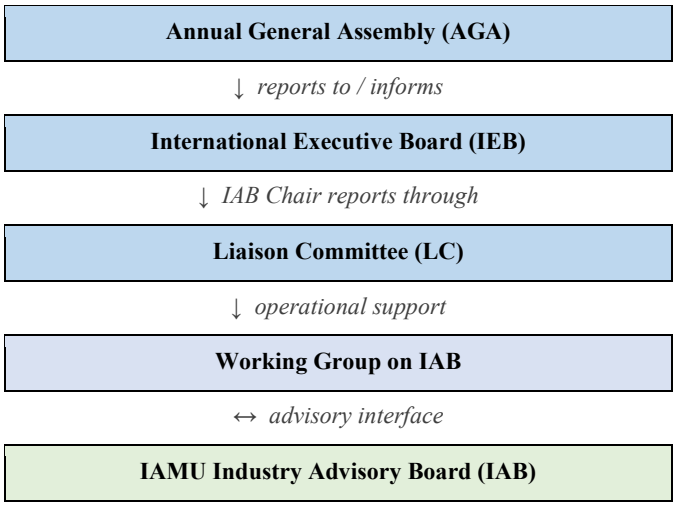
4. Governance Design of the IAMU-IAB

4.1 Institutional Positioning and Reporting Structure

Figure 2 illustrates the proposed governance integration of the IAMU-IAB. Recommendations flow through the IAB Chair to the Liaison Committee Head and thence to the International Executive Board, which

may act on advisory outputs or transmit insights to the Annual General Assembly. This chain preserves the advisory character of the mechanism while ensuring accountability.

Figure 2. Proposed Governance Integration of the IAMU-IAB.



The IAB operates under, not alongside, the Liaison Committee. This integration point requires no amendment to the Basic Agreement, maintains governance stability, and ensures advisory outputs flow through an established channel with direct access to the IAMU leadership.

4.2 Membership Structure and NGO-to-NGO Approach

Candidate organizations are drawn exclusively from international NGOs holding IMO consultative status. This model was adopted because such NGOs provide sector-wide rather than individual corporate perspectives; the IMO requires them to be genuinely international in scope; and the approach aligns with the IAMU's own NGO status at IMO while reducing conflicts of interest. Alternative configurations were considered and rejected: a mixed NGO–corporate board risks conflict-of-interest dynamics inconsistent with the IAMU's NGO consultative status; regional industry councils fragment the global perspective the IAMU's mandate requires; rotating company representatives reintroduce the personnel-dependent continuity risks the project sought to avoid; and thematic panels (e.g. decarbonization, autonomous shipping) are complementary rather than foundational, and may be convened by the IAB once established. The NGO-to-NGO model was selected because it best balances global representativeness, mission alignment, institutional accountability, and independence from commercial interests.

The Charter specifies that IAB members must be formally designated representatives of their parent organizations, not individuals in a personal capacity, ensuring institutional accountability and reducing personnel-dependent continuity risks.

4.3 Operational Framework and Risk Management

The IAB meets twice annually: in the spring (online or in person) and in the autumn, preferably alongside the IAMU Annual General Assembly. Notices are issued at least four months in advance and minutes circulated within one month. The SOP handbook covers recruitment and onboarding, meeting administration, documentation, reporting, and risk management.

Identified operational risks include low NGO participation, delays in representative nomination, and sustainability challenges after project completion. The model also carries design tensions requiring active management: representational imbalance, where better-resourced NGOs may dominate discussions; the complexity of coordinating multiple international organizations; advisory fatigue if recommendations are not visibly acted upon; conflicting stakeholder agendas; and the coordination resources required of the Secretariat and Liaison Committee. Mitigation measures include virtual participation, a structured onboarding package, a

clear value proposition for members, balanced representation criteria, transparent agenda-setting, and mandatory periodic Charter review.

5. Consultation Outcomes and External Validation

The London visits in November 2025 tested institutional receptivity among three internationally representative maritime organizations. At the Institute of Chartered Shipbrokers, discussion identified a concrete gap: engagement with maritime universities had been bilateral and project-specific, and a formalized multi-institutional platform would address what individual partnerships cannot. At the International Chamber of Shipping, representatives pointed to decarbonization timelines, the competency demands of autonomous vessels, and the need for continuous rather than periodic industry input into academic governance. This feedback aligns with Rybnicek and Königsgruber's (2019) finding that relational engagement outperforms transactional models for long-term curriculum alignment. At the IMO, the NGO-to-NGO collaboration model was assessed as compatible with the IMO's framework for organizations in consultative status, and the advisory-only positioning was confirmed as appropriate for the IAMU's institutional context.

The formal IEB presentation drew substantive governance feedback on terminology, mandate scope, and implementation sequencing. The principal recommendation, a time-bound working group before full institutionalization, reflects a documented tendency among established organizations to favor phased structural change over immediate formalization (Davis, 2006; Genheimer and Shehab, 2009; McIntyre and Fox, 2014). This was incorporated into the implementation roadmap without modification.

6. Discussion

6.1 Contributions to Governance Practice

The project makes three contributions to governance practice. First, action research is shown to serve as a methodology for governance design, producing implementation-ready documents developed iteratively with institutional leadership rather than merely diagnosing problems. Second, the NGO-to-NGO model suits associations balancing industry engagement with representational independence. Third, the Power–Interest matrix offers a replicable, evidence-based approach to partner selection.

6.2 Implications for Maritime Education and Training

The structural gap addressed by BRIDGE-IAB is not unique to the IAMU. The MET literature consistently identifies misalignment between curricula and evolving industry requirements as a systemic challenge, driven partly by the speed of maritime transformation and partly by a governance problem: the absence of institutional channels through which industry knowledge can flow regularly and accountably into educational decision-making (Caesar, 2024; Rybnicek and Königsgruber, 2019). The IAMU-IAB addresses this at the global level, creating the conditions for more responsive, continuously updated MET systems.

6.3 Transferability and Limitations

The model is transferable to other international academic associations. Its core principles — advisory-only status, mission-aligned membership, governance integration, formal operating procedures, and a monitoring framework — adapt across sectoral contexts, and the Power–Interest methodology applies wherever international organizations hold IMO-equivalent consultative status.

Empirical assessment of operational effectiveness must await IEB approval and phased implementation, which provides the basis for future longitudinal research. Further limitations apply: external validation rests on only three consultations; as an internal IAMU project the design carries potential institutional bias; input came primarily from the IAMU leadership and Secretariat rather than the broader membership; and channelling input through NGOs may not fully capture individual commercial perspectives.

7. Conclusion

The BRIDGE-IAB Project has produced a governance design and implementation roadmap for the IAMU-IAB. Through an action research–informed process combining literature review, institutional diagnosis, stakeholder analysis, governance document development, IEB consultation, and direct engagement

with leading maritime organizations, the project provides an IAB design whose governance compatibility and stakeholder receptivity have been demonstrated. Operational viability and financial sustainability are addressed at the design level through the proposed Charter, SOP, and risk-management provisions, and remain to be confirmed during phased pilot implementation.

The project moves the IAMU's industry engagement model from informal, relationship-driven interaction to institutionalized, mechanism-based collaboration, as the Tokyo Statement mandates. The governance design is deliberately conservative: advisory-only, integrated under the Liaison Committee, requiring no change to the Basic Agreement, and subject to periodic review. Its strategic potential, however, is considerable: structured, accountable, and continuous dialogue between the world's foremost maritime academic network and globally representative industry bodies.

In a sector transforming faster than educational institutions have historically matched, such governance innovation is not peripheral; it is a precondition for institutional relevance.

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Salvage of Remotely Operated Autonomous Vessels – Who is entitled to Salvage Reward according to the Salvage Convention and the Law of Salvage

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Abstract: A Law of Salvage has ancient roots in Law of Rhodes from which it was found by the Romans who organised it to be based on principles like Negotiarum Gestio and Versio in rem. Law of Salvage was developed from principles to national laws and harmonized later by two international Salvage Conventions in 1910 and 1989.

Salvage agreements became more common in the late 1800s with the introduction of steam and engine-powered tugboats, and the first versions of the LOF standard agreement were introduced already at that time. In the case of unmanned vessels (previously mainly barges) and abandoned vessels, the right to the reward was granted to the salvor who was the so-called "first salvor". Based on the right of the first salvor, salvage operations were initiated on the salvors own initiative and if they succeeded in them (No Cure – No Pay) they were entitled in salvage reward. The owner or representative of the salved vessel had to refuse the help of the salvor who arrived at the scene. However, if the vessel was not manned, a representative was needed to handle the refusal, expressing the negative will of the owner that his vessel would be salved – Otherwise the salvor who was first in place to start salvage operations would be entitled to salvage reward. The possible refusal was often due to the fact that the owner of the abandoned vessel had already signed an agreement with the owner of the ship on its way to salve the vessel.

How can an autonomous ship that is in danger choose its salvors ? Or is it the salvors' free game? Previously, it was required that a ship that has been abandoned can be salved by the first person to arrive at the scene to start rescue operations. How is a ship that moves independently considered abandoned? The crew of an abandoned vessel is normally not considered to be entitled to a salvage reward for salving their own vessel, unless the master has ordered the vessel to be abandoned and the crew has left the vessel without the hope of returning to it. How should the actions of the crew in and from the remote control centre and the right to the salvage award be assessed with regard to a remotely controlled vessel? Are they entitled to a salvage reward after losing contact with the ship? Are they entitled to a salvage reward only when they physically board a ship for rescue purposes or when they land from a helicopter? Does the same ROC apply to an engineer who takes care of the ship's technology from a remote control center ? or the owner of the cargo assists in salving his/hers own cargo by providing expert information/assistance ? Is the task force sent to repair the ship's systems on site entitled to a salvage award and share of the ship and its cargo?

The crew's share of the salvage award for the salvaging vessel is determined in accordance with rules of the Maritime Act. How are these rules interpreted if the crew operates from one or more remote control centres? How is the reward distributed in such a situation when the salvage is carried out by another remotely operated vessel (e.g. sister vessel) that may be steered by the same remote operator as the vessel to be salved. The salvage regulations have clearly not been thought through to the end with regard to remotely piloted vessels. The article seeks answers and interpretations to the above questions.

Keywords: Law of Salvage; Salvage Contracts; Autonomous vessel, Remote Operation, Salvage Reward.

1. Introduction

Law of Salvage has ancient roots in Law of Rhodes from which it was found by the Romans who organised it to be based on principles like *Negotiarum Gestio* and *Versio in rem*. Law of Salvage was developed from principles to national laws and harmonized later by two international Salvage Conventions in 1910 and 1989. The first of these conventions was drawn up because national laws had become very different and had previously departed significantly from the principles of uniform Roman law. The latter, the 1989 Convention, was essentially a modernisation of the previous Convention and sought to establish rules encouraging environmental protection and the salvors to be rewarded by both salvage award and special compensation regime in case the reward did not cover the cost of the salvor.

2. Salvage agreements

Salvage agreements became more common in the late 1800s with the introduction of steam and engine-powered tugboats, and the first versions of the LOF standard agreement were introduced already at that time. In the case of unmanned vessels (previously mainly barges) and abandoned vessels, the right to the reward was granted to the salvor who was the so-called “first salvor”. Based on the right of the first salvor, salvage operations were initiated on the salvors own initiative and if they succeeded in them (No Cure – No Pay) they were entitled in salvage reward. The owner or representative of the salved vessel had to refuse the help of the salvor who arrived at the scene. However, if the vessel was not manned, a representative was needed to handle the refusal, expressing the negative will of the owner that his vessel would not be salved – Otherwise the salvor who was first in place to start salvage operations would be entitled to salvage reward. The possible refusal was often due to the fact that the owner of the abandoned vessel had already signed an agreement with the owner of the ship on its way to salve the vessel.

3. How can an autonomous ship that is in danger choose its salvors ? Or is it the salvors' free game?

Previously, it was required that a ship that has been abandoned can be salved by the first person to arrive at the scene to start salvage operations. How is a ship that moves independently considered abandoned? The crew of an abandoned vessel is normally not considered to be entitled to a salvage reward for salving their own vessel, unless the master has ordered the vessel to be abandoned and the crew has left the vessel without the hope of returning to it. How should the actions of the crew in and from the remote control centre and the right to the salvage award be assessed with regard to a remotely controlled vessel in this respect? Are they entitled to a salvage reward after losing contact with the ship? Are they entitled to a salvage reward only when they physically board a ship for salvage purposes or when they land from a helicopter? Does the same ROC apply to an engineer who takes care of the ship's technology from a remote operation centre ? Is the task force sent to repair the ship's systems on site entitled to a salvage award and share of the ship and its cargo? or the owner of the cargo who assists in salving his/hers own cargo by providing expert information/assistance ? This particular question has been answered in a case Sava Star which could be interpreted with analogy to autonomous vessel:

> *A cargo of 2,951 mt of complex fertiliser NPK in bulk was carried on the defendant's vessel, Sava Star, from Heroya, Norway, to Immingham, England. The plaintiff was the cargo owner and named consignee in the bill of lading. The vessel was voyage chartered to Norsk Hydro AS (Norsk Hydro), the plaintiff's parent company. The cargo began to decompose during the voyage, causing fire and fumes. The master agreed LOF 90 with a contractor, United Towing Ltd, on behalf of the owners of the vessel, its cargo, freight, bunkers, stores, and any other property. The vessel and the cargo were salved through the services provided by the contractor and the plaintiff. The contractor was awarded salvage remuneration by an arbitrator appointed under LOF 90.*
>
> *The question before the Court was whether, assuming that the services rendered by the plaintiff were in the nature of salvage services and that they were successful or contributed to the success, the plaintiff, as cargo owner, was entitled in law to salvage remuneration.*
>
> *Clarke J considered the relevant cases and found that the following propositions have been accepted by both practitioners and judges over a very long period: (1) A shipowner is not entitled to claim salvage against itself. (2) Where ship and cargo are salved by a vessel in the same ownership as the salved ship, the master and crew of the salving ship are entitled to salvage against the owners of the salved ship and the owners of its cargo. (3) In such cases, the shipowners are entitled to salvage against the owners of the cargo on the salved ship unless the casualty which*

necessitated the salvage services was wholly caused by an actionable breach of contract on the part of the plaintiffs. (4) Subject to (1) above, the fact that salving and the salved ships are in common ownership or common management is relevant to the quantum of the salvage award.

There are no rigid categories of salvor; they include any volunteer who renders service of a salvage nature; and there is no reason why they should not include cargo owners who personally rendered salvage services.

4. When can an autonomous vessel considered abandoned and in need of assistance/salvage?

When autonomous/remotely controlled vessel is in trouble and cannot be taken over or operated remotely by the Master or operator in the ROC, it is in state where it needs assistance or salvage. Salvage Convention 1910 was named “The 1910 salvage convention's original name is the Convention for the Unification of Certain Rules of Law respecting Assistance and Salvage at Sea.” This indicates that the same principles apply also in these borderline cases where assistance and salvage are close to each other and are conceptually mixed. Traditionally before the convention assistance was in many nations considered something that normally belonged to seafaring and no reward was due. In some Civil Law Countries, like France, the law traditionally made a distinction where "assistance" referred to helping a vessel whose crew remained on board, while "salvage" (*sauvetage*) referred to rescuing an abandoned vessel.

In the 1910 Brussels Salvage Convention, no legal distinction is drawn between "assistance" and "salvage". Article 1 explicitly states that both terms are subject to the same provisions, regardless of the type of service or the waters in which they occur. The difference of the terms is not considered again in the 1989 convention, but it has not changed and the case practice has remained the same basing still on the cases given on the basis of 1910 convention. In Finland still in 1986 (under the 1910 convention) in the case *Kuurtanes*, a vessel was not entitled to salvage reward when it freed another vessel from ice which was moving towards a reef. The supreme court considered this action as normal assistance that belonged to the seafaring practices that are not entitled to be rewarded as salvage. The vessel had suddenly stuck into ice which was moving to a rocky area.

The need for either assistance or salvage in relation to autonomous vessel seems to be the same issue which does not depend on if the vessel is “abandoned” or not. If the vessel is not in control of the ROC and it is in danger, even slightly moderate on, it needs to be salved by a salvor. When the salvor takes the autonomous vessel in control, the first salvors right is established and the salvor has the right to complete the salvage work in a way that he is able to use the vessel as guarantee to obtain his salvage reward. In this case, even if the control of the ROC is again established, according to the law of salvage the salvor has the right to take the salved object in a place of safety and take care of it as a security until his reward is secured through other means. If the vessel owner – after ROC has retained control – arranges a guarantee to the salvor, there is no obstacle for releasing the autonomous vessel to its owners as the salvors right has been guaranteed by other means.

5. Salvor – Master and Crew

Under current maritime law, the party that performs the salvage operation—whether a human-crewed vessel, a remotely operated vessel, or an autonomous vessel—may be entitled to a salvage reward, provided the operation meets the legal criteria for salvage. The master’s share goes to the person who exercises command over the salvage operation—even if they do so from a remote operation centre. The share may be reduced because the remote master faces no personal physical risk, but their skill and responsibility still justify a distinct portion of the reward. This is quite rational interpretation of the law but it is not based on any existing case law as there is none until this article is left to publisher.

The crew's share of the salvage award for the salvaging vessel is determined in accordance with rules of the Maritime Act. A remotely operated vessel is treated similarly to a crewed vessel: The remote operator does not personally receive the reward. The company employing the operator or owning the vessel receives it. This is consistent with how salvage rewards are handled for crewed commercial salvage vessels today.

How are these rules interpreted if the crew operates from one or more remote control centres? How is the reward distributed in such a situation when the salvage is carried out by another remotely operated vessel (e.g.

sister vessel) that may be steered by the same remote operator as the vessel to be salved. The salvage regulations have clearly not been thought through to the end with regard to remotely piloted vessels.

The International Convention on Salvage 1989 does not require the salvor to be a human-crewed ship. The Convention focuses on the act of rendering voluntary and successful assistance to a vessel in danger, not on the nature of the salvor. Scholarly analysis confirms that a Maritime Autonomous Surface Ship (MASS) performing salvage can qualify as a salvor under the Convention.

6. Legal person behind

Because an autonomous or remotely operated vessel cannot hold legal rights itself, the entitlement belongs to the legal person who owns, operates, or controls the autonomous vessel. This may include: 1) The vessel owner (most common) 2) The operator or company controlling the remote-operation center 3)The charterer, if contractually responsible for the salvage activity (usually through time charter agreement), 4) An insurer, if subrogated after paying losses.

This follows the general principle that salvage reward is owed to the party that provides the salvage service, and in the case of unmanned systems, that party is the human legal entity behind the system.

7. Conclusions

Several studies note that MASS operations expose gaps in the Salvage Convention, especially regarding: 1) How to evaluate the risk taken by an unmanned salvor (traditionally a major factor in reward calculation) 2) Whether reward factors should be adjusted because autonomous systems reduce human risk 3) How to treat AI-driven decision-making in assessing “skill and efforts” of the salvor ?

The absence of a crew does not prevent entitlement, though the criteria for calculating the reward may need future reform. As we have learned our lesson from the previous revision of the salvage convention, this should not be made in a way of reforming the convention itself. When the Amoco Cadiz accident in 1978 showed the backwardness of international regulation and it was decided to remedy it by amending the Convention, the work took forever. The public was established in 1989 and it was not implemented until 1996. Its implementation in Finland took well into the 2000s, and yet the regulation soon had to be supplemented with market-based solutions. In terms of the need for change, autonomous shipping corresponds roughly to the extent that the 1989 amendments to the Convention were aimed at. However, there is no time for a similar process, as international autonomous shipping for cargo vessel traffic will begin this year when the MASS code is completed.

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Assessment of the effectiveness of the Maritime Labour Convention, 2006 in enforcing seafarers' rights in the global and digital maritime labour market

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Abstract: The Maritime Labour Convention, 2006 (MLC 2006) remains a key international instrument for protecting seafarers' rights and an important pillar of the regulatory framework for shipping. This article assesses the effectiveness of the MLC 2006 in the context of a transforming shipping industry. The analysis considers classic enforcement challenges arising from the fragmented responsibility in transnational shipping, as well as new tensions caused by the digitalisation, work automation, decarbonisation, and the development of autonomous ships. The study is based on a normative interpretation of the MLC 2006, the literature on Maritime 4.0, Maritime Autonomous Surface Ships (MASS), and the green transition, and data from Port State Control reports of selected Memoranda of Understanding (MoU). The article assumes that the key question is not only whether the catalogue of seafarers' rights remains relevant, but rather whether the current implementation model can effectively protect seafarers in a changing work environment.

The study concludes that the MLC 2006 retains its axiological relevance; however, its effectiveness is weakened by persistent enforcement gaps and insufficient consideration of digitalisation, the green transition, and changing competency requirements, indicating an implementation gap in transforming shipping.

Keywords: MLC 2006; seafarers' rights; enforcement; digitalisation; autonomous shipping.

1. Introduction

The MLC 2006 continues to serve as the primary instrument for safeguarding seafarers' rights; however, it is now operating within the context of a profound transformation of the shipping industry. The maritime sector is currently experiencing simultaneous pressures of decarbonisation, digitalisation, automation and the reorganisation of operational models. Concurrently, ships are being transformed into cyber-physical work environments, characterised by the utilisation of data, remote monitoring and complex human-technology interactions (UNCTAD, 2025). The research problem is therefore no longer limited to the question of whether working conditions comply with MLC standards, but also encompasses the question of whether the Convention is being effectively implemented in the face of new challenges associated with the sector's transformation.

These changes affect not only shipping companies but also the very nature of work at sea itself (Sullivan *et al.*, 2021). Digitalisation has increased reliance on information systems, automation has shifted the seafarer's role towards monitoring and responding to exceptions, and the green transition has required the handling of new fuels, energy systems and safety procedures. Concurrently, the emergence of MASS and remote operations centres points to further changes in the relationship between people, ships and shore (Ichimura *et al.*, 2022; IMO, 2023; Xu and Guedes Soares, 2026). Consequently, MET institutions face challenges related to the development of training pathways that prepare students for work in a digital and low-carbon environment. These challenges include the ability to safely operate new technologies, resilience to technostress, and maintaining well-being in conditions of increasing operational complexity (IMO, 2023; Koundouri, 2024; Bayrak, 2025; Belabyad, 2025).

The objective of this article is to assess the effectiveness of the MLC 2006 in enforcing seafarers' rights in the context of the multifaceted transformation of shipping. The analysis focuses on the relationship between the normative relevance of the MLC 2006 and its practical effectiveness in the changing maritime working environment, with particular emphasis on the role of the MET.

2. MLC 2006 as the normative basis for the protection of seafarers

The MLC 2006 was adopted as a comprehensive instrument intended to replace the previous, fragmented system of labour standards at sea. Its significance lies in combining a catalogue of seafarers' fundamental rights with mechanisms for their implementation and enforcement. The normative core of the Convention is defined primarily by Articles III and IV, which cover freedom of association, the elimination of forced and child labour, the prohibition of discrimination, and the right to a safe workplace, decent terms and conditions of employment, health protection, medical care, social security, and rest (ILO, 2022a).

The broad personal and functional scope of the Convention is also important. In principle, MLC 2006 covers all seafarers and all ships falling within its scope. The concept of a shipowner has been defined functionally so as to assign responsibility to the entity that actually organises employment and working conditions on board the ship. Consequently, the Convention more effectively addresses the transnational and multi-actor structure of contemporary shipping (ILO, 2022b; ILO, 2022c).

Article V is of particular importance, as it links substantive rights with the certification system, Flag State control, Port State Control inspections, and complaint procedures. In this sense, the MLC 2006 is not merely a catalogue of social standards, but also a compliance instrument. Its relevance was further confirmed by the amendments adopted in 2025, which strengthen the protection of seafarers, *inter alia*, by facilitating repatriation on a non-discriminatory basis, regulating the right to shore leave, emphasising the treatment of seafarers as key workers, and strengthening guarantees of fair treatment (ILO, 2025). These changes demonstrate that the Convention can be developed adaptively, although they do not eliminate all gaps related to digitalisation and the development of autonomous shipping (UNCTAD, 2025).

3. The issue of enforcement in global shipping

The extensive formal scope of protection provided for in the MLC 2006 does not automatically guarantee an equally high level of protection in practice. The primary issue concerning the Convention's effectiveness is therefore not simply whether it guarantees adequate rights, but whether the system of Flag State control, certification, complaint procedures, and Port State Control inspections actually ensures real and reasonably consistent protection (UNCTAD, 2025).

A primary factor contributing to weakened effectiveness is the inherent structural complexity that characterises contemporary shipping practices. In practice, responsibility for a ship may be divided between the legal owner, the ship manager, the commercial operator, the charterer, the crewing agency and the flag administration. Such a structure favours the diffusion of practical responsibility. While a seafarer may formally remain under protection, it is challenging to precisely identify the entity responsible for ensuring adequate working conditions, rest periods, health protection, and access to legal remedies (ILO, 2022c).

Table 1. Number of abandoned ships and seafarers.

Year	Abandoned ships	Abandoned seafarers
2022	113	1 555
2023	132	1 676
2024	312	3 133
2025	410	6 223

Source: ITF

Consequently, despite the Convention having been in force for more than a decade, the situation of some seafarers has not improved substantially. Evidence for this can be found in data on ship abandonments (see Table 1) and the results of Port State Control (PSC) inspections in selected regional PSC systems.

The selection of Memoranda of Understanding was based on two criteria: the number of inspections carried out and the availability of comparable data in the annual reports. The Paris MoU, Tokyo MoU and

Abuja MoU were selected for analysis. The study was based on the reports from the last five years for each of the selected Memoranda of Understanding (MoU). The scope of the study enabled the identification of the main trends concerning non-compliance with the MLC 2006.

Before conducting a detailed analysis of the three selected regions, the PSC inspection effectiveness across a greater number of regions should be examined in order to outline the broader context. The analysis was therefore extended to six regional PSC organisations: the Abuja MoU, the Black Sea MoU, the Mediterranean MoU, the Viña del Mar Agreement, the Paris MoU, and the Tokyo MoU. As illustrated in Figure 1, the outcomes of the inspections conducted in 2024 are presented, based on the Annual Reports of all the aforementioned regions.

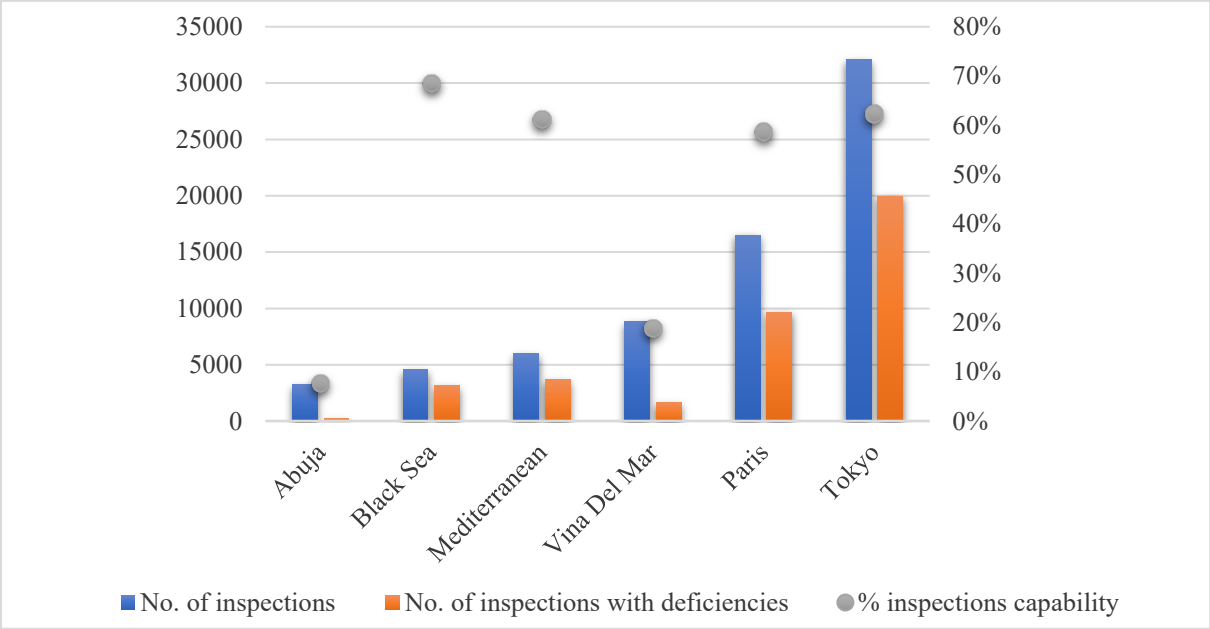


Figure 1. PSC inspections effectiveness in 2024
Source: own elaboration of the reports published by the Abuja MoU, the Black Sea MoU, the Mediterranean MoU, the Viña del Mar Agreement, the Paris MoU, and the Tokyo MoU during the 2020-2024 period.

The number of inspections varies significantly across different regions. The Tokyo MoU has the highest number of annual PSC inspections, exceeding 30,000. The Paris MoU encompasses a total of over 15,000 inspections, the Viña del Mar Agreement covers approximately 9,000 inspections, and the Mediterranean and Black Sea regions each account for around 5,000 inspections. The scope of the Abuja Memorandum of Understanding (MoU) encompasses approximately 3,000 inspections, which is a fraction of the 30,000 inspections provided by the Tokyo MoU. At this point, the effectiveness of inspections in the regions can be assessed. The subsequent analysis will determine the number of inspections that revealed any deficiencies.

The results show that inspections conducted under the Abuja MoU and the Viña del Mar Agreement exhibit a markedly lower level of effectiveness, as evidenced by the Abuja MoU's 7.7% inspection rate resulting in deficiencies and the Viña del Mar Agreement's 18.8% inspection rate resulting in deficiencies. In contrast to these two regions, in all four remaining regions 60–70% of inspections reveal deficiencies. It is difficult to accept the premise that all vessels in these two regions meet the highest standards, thus other factors must be considered as contributing to these results. It is conceivable that the two regions exhibiting the lowest effectiveness may adopt a more liberal approach to PSC inspections, or alternatively, they may provide crews with the opportunity to rectify deficiencies prior to the completion of the inspection. Knowing the effectiveness of each region, it is now possible to ascertain the number of MLC deficiencies recorded in each region during the PSC inspection in 2024 (Figure 2).

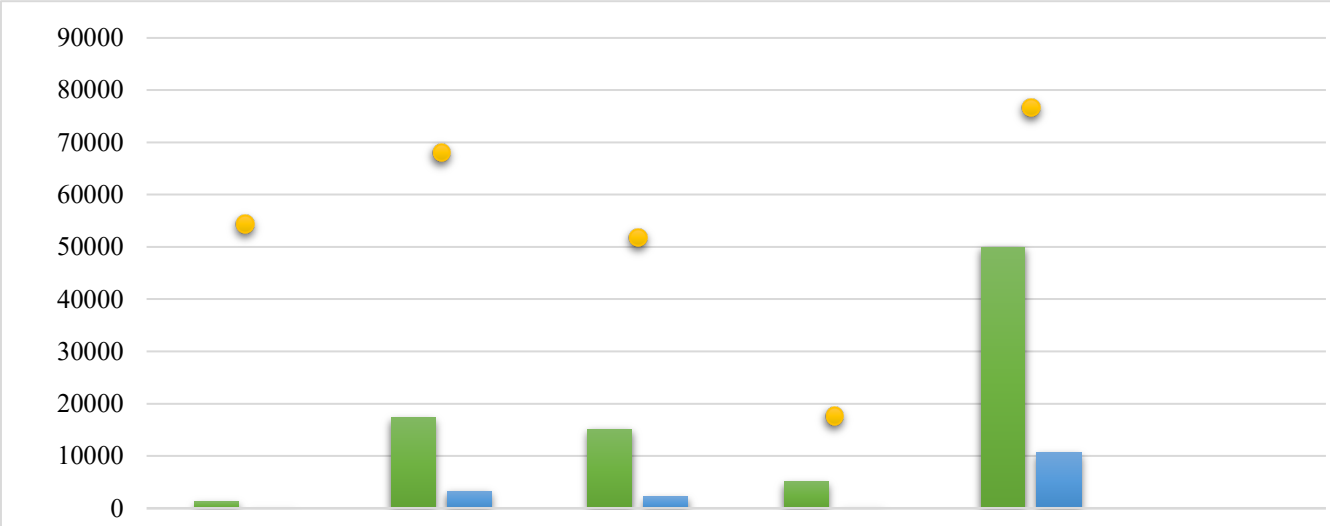


Figure 2. PSC MLC deficiencies, 2024
Source: own elaboration of the reports published by the Abuja MoU, the Black Sea MoU, the Mediterranean MoU, the Viña del Mar Agreement, the Paris MoU, and the Tokyo MoU during the 2020-2024 period.

As in the previous analyses, the regions with the lowest inspection and enforcement capacity (the Abuja MoU and the Viña del Mar Agreement) report the fewest deficiencies. The remaining regions with higher inspection potential record substantially larger numbers of deficiencies, which is closely related to the greater number and intensity of inspections conducted. The highest numbers of deficiencies are reported within the Tokyo MoU and the Paris MoU regimes. Nevertheless, the present study aims to analyse the pattern of MLC deficiencies across all regions. It is evident that the Viña del Mar Agreement region exhibits the lowest number of MLC deficiencies, accounting for a mere 5% of all deficiencies documented during PSC inspections in 2024. Across all other regions, the prevalence of MLC deficiencies ranges from 10% in the Tokyo MoU to 21% in the Paris MoU. The present study aims to deepen the analysis of three MoU regions: the Tokyo MoU, the Paris MoU, and the Abuja MoU. The Tokyo MoU and the Paris MoU have the highest number of inspections and the highest number of deficiencies. The Abuja MoU is noteworthy because despite its relatively low inspection effectiveness, the number of identified MLC deficiencies remains relatively high.

Table 2. Percentage of MLC deficiencies as a proportion of total deficiencies reported by Abuja MoU, Paris MoU, and Tokyo MoU, 2020-2024.

	Abuja MoU			Paris MoU			Tokyo MoU		
Year	Total defs.	MLC defs.	MLC share	Total defs.	MLC defs.	MLC share	Total defs.	MLC defs.	MLC share
2020	973	124	12.7%	28372	5834	20.6%	34924	5296	15.2%
2021	1274	152	11.9%	36367	7585	20.9%	39838	5773	14.5%
2022	1305	190	14.6%	47569	10016	21.1%	46769	6034	12.9%
2023	1384	234	16.9%	47540	9569	20.1%	75867	7246	9.6%
2024	1254	189	15.1%	49958	10655	21.3%	77526	8193	10.6%

Source: own elaboration of the reports published by the Abuja MoU, the Paris MoU, and the Tokyo MoU during the 2020-2024 period.

As illustrated in Table 2, there has been a marked increase in the identification of MLC deficiencies across three selected regions over the past five years (2020–2024).

The prevalence of deficiencies varies significantly across different geographical regions and has increased over time. Under the Tokyo MoU, the number of deficiencies increased by more than 100% between 2020 and 2024. This is attributable to the increased number of inspections rising from 19,416 in 2020 to 32,054 in 2024. The growth of deficiencies in the Paris MoU is also increasing significantly, but not to the same extent as in the Tokyo MoU (by 76% in the Paris MoU). However, the data from the Abuja MoU reveal a different pattern. The number of deficiencies has increased marginally and has remained relatively stable

between 2021 and 2024 (with fewer deficiencies in 2024 than in 2021), despite a rise in the number of inspections (from 2,085 inspections in 2020 to 3,204 inspections in 2024). However, it is important to remember that, as we saw earlier, the inspection capability in the Abuja MoU is the lowest of all the regions analysed. The following section analyses the number of MLC deficiencies across all three regions.

The number of MLC deficiencies in the Tokyo MoU is increasing year by year, but the share of MLC deficiencies is slowly decreasing from 15% in 2020 to 10.6% in 2024 (9.6% in 2023). In the Paris MoU, MLC deficiencies are also increasing, but over the past three years the level has been almost the same. If we look at the share of MLC deficiencies in the Paris MoU, the number is quite high and most likely remains the same, around 21%. Data from the Abuja MoU once again show otherwise. MLC deficiencies are very low, but the share of MLC deficiencies has increased slightly from 12% in 2020–2021 to 15–16% over the past two years.

Several conclusions can be drawn from these data. In the Tokyo MoU and in the Paris MoU, awareness is very high, with the number of MLC deficiencies showing a thorough approach to MLC matters. We can be tempted to conclude that the work of PSC inspectors in the Tokyo MoU has started to bring positive results and that the MLC standard on vessels has recently increased. The situation in the Paris MoU shows the high awareness of PSC inspectors regarding MLC-related issues; however, the MLC standard of the vessels remains unchanged. It is good to see that awareness of MLC-related issues is slowly increasing in the Abuja MoU.

4. Digitalisation, the green transition, and autonomous shipping as drivers of change in the working environment

The literature on Maritime 4.0 demonstrates that contemporary digitalisation is characterised by the increasing integration of data into decision-making processes, the development of monitoring systems, the optimisation of operations, and the expansion of decision-support tools. The object of this transformation is therefore not only the business model of shipping companies or the logistics chain, but also the nature of the work carried out on board (Sullivan *et al.*, 2021).

From the perspective of seafarers' rights, the most salient point is that digitalisation and automation do not eliminate humans from the shipping system; rather, they redefine their role. Studies on shipping companies and autonomous shipping consistently show that seafarers' tasks are increasingly shifting towards system management, monitoring operations, handling exceptional situations, and responding to system degradation (Ichimura *et al.*, 2022; Zhou *et al.*, 2025).

The green transition, encompassing new fuels, energy systems, and efficiency requirements, overlaps with digitalisation and, together with it, creates a new working environment that requires digital, environmental, and managerial competencies (Koundouri *et al.*, 2024).

The literature on MASS and autonomous shipping includes forecasts suggesting a reduction in crew numbers or decreased reliance on onboard crew. However, recent research suggests that, rather than a simple "elimination of humans", a reconfiguration of crew roles and a shift of some functions towards supervision, intervention and shore-based support are more likely (Xu and Guedes Soares, 2026). Research on autonomous shipping and the reform of Maritime Education and Training (MET) confirms that operational, digital, and maritime skills remain crucial even in highly automated environments (Tijan *et al.*, 2021; Belabyad *et al.*, 2025).

The transformation is not neutral from the perspective of seafarers' rights. The ship is becoming not only a technologically enhanced workplace, but also a monitored, data-driven, and potentially more cognitively demanding environment. Digital tools may enhance productivity and safety, but they may also intensify surveillance, blur the boundary between work and rest, and increase seafarers' dependence on interfaces, alerts, and remote data systems.

5. The implementation gap in the era of digitalisation and the green transition

The primary challenge confronting the MLC 2006 in the context of digital shipping and the green transition in the shipping sector is one of implementation. Its normative core remains stable. The difficulty lies rather in the fact that the maritime working environment is changing faster than traditional approaches to interpreting and enforcing the rights contained in the Convention (ILO, 2022c). Consequently, it is more precise to refer to an 'implementation gap'.

This gap has at least two levels. The first is classical: even within the conventional model of global shipping, protection is not implemented uniformly, as evidenced by regional differences in PSC practice, persistent shortcomings, and phenomena such as crew abandonment. The second level is new: digital shipping, the green transition, and emerging autonomous operations create risks that are much more difficult to capture within the traditional inspection model (Sullivan *et al.*, 2021; Zhou *et al.*, 2025).

Consequently, the response should not be to dismiss the MLC 2006 as obsolete. A more convincing response lies in dynamic interpretation and adaptive implementation (ILO, 2025; UNCTAD, 2025). Under such an approach, the right to a safe and secure workplace should be understood as encompassing occupational safety in the cyber-physical environment; the right to rest must include a genuine opportunity for cognitive recovery; and the right to health protection must encompass technostress, digital fatigue, and the psychosocial effects of constant monitoring and automation (Bayrak and Muslu, 2025; Ma and Liao, 2025).

An important element of closing this implementation gap is Maritime Education and Training (MET). MET institutions play a key role in this regard. Institutions responsible for maritime education and training can no longer limit themselves to transmitting traditional minimum technical knowledge. They must adapt both the content and methods of teaching. MET should therefore combine knowledge of the rights arising from the MLC 2006 with preparation for work in a digital and low-carbon environment, including through methods such as case-based learning using real-life cases, e-learning, innovative projects, mentoring, work placements, collaboration with industry, and flexible forms of education and assessment (Koundouri *et al.*, 2024; Belabyad *et al.*, 2025).

In this sense, maritime education is not external to labour protection; it is a part of it. Effective protection does not begin only at the stage of inspection or complaint submission. It also begins at the stage of enabling future seafarers to recognise their rights, identify new forms of harm, and understand how to respond when those rights are threatened in workplaces undergoing technological transformation.

6. Conclusions

The analysis shows that the traditional enforcement problems – the diffusion of responsibility, the uneven quality of supervision, and the limitations of a documentation- and certification–based model – have not disappeared. They are now compounded by new challenges such as technostress, cognitive overload, operational dependence on cyber systems, and rising competency requirements.

This does not, however, mean that the Convention has become normatively obsolete. It is more accurate to state that the MLC 2006 remains adequate at the level of principles, but requires dynamic interpretation, more consistent enforcement, and the supplementation of implementation practices with a digital and environmental perspective. This also applies to MET, since the effective protection of seafarers' rights begins already at the stage of preparing them for work in a new technological environment. Only such a combination of law, implementation practice, and education can fully realise the human-centred character of labour protection at sea (Thanopoulou *et al.*, 2022; SkillSea, 2023; ILO, 2025; Karimpour and Figari, 2025; UNCTAD, 2025).

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Fairness culture in maritime sector: Bridging the legal and digital divides in near-miss reporting

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Abstract: Although the shipping industry increasingly emphasises safety culture, the legal and institutional foundations required for fair reporting systems remain underdeveloped. This study uses semi-structured interviews with maritime authorities, shipping managers, and seafarers to examine fairness culture in the context of near-miss reporting. Existing governance arrangements and persistent gaps in legal protection and digital governance are explored. It was found that current international rules provide limited enforceable guidance on fairness culture. Safety Management Systems are more focused on procedural compliance than on psychological safety, inclusion, and organisational learning. Weak anti-retaliation protections also reduce the willingness of onboard seafarers to report risks. In addition, the digitalisation of near-miss governance has introduced fragmented data standards, uncertain evidentiary value of electronic reports, and limited algorithmic due process. As a result, technical conformity may be reinforced, while critical human-factor risks remain insufficiently addressed. Therefore, reforms should be advanced at both international and domestic levels to strengthen legal certainty, improve organisational learning, and support a more inclusive maritime workforce.

Keywords: Maritime safety; Marine policy; Fairness culture; Near-miss reporting; Semi-structured interviews

1. Introduction

As digital tools become embedded in daily vessel operations and safety management, the maritime industry's focus is shifting from technical compliance toward organisational behavior and institutional safeguards (Rajapakse, et al., 2021). Maritime governance is undergoing a profound transformation. The integration of artificial intelligence, big data, and the Internet of Things now enables smarter route optimisation and real-time emissions monitoring, providing powerful levers for greener and safer operations (Tadros, et al., 2026). However, enhanced safety outcomes cannot be assumed solely on the basis of technological improvements. In areas such as near-miss detection, risk management, and the feedback of frontline experience, the critical question is whether institutional frameworks encourage proactive reporting and tolerate honest mistakes so as to drive organisational learning.

The concept of a 'fairness culture' is gaining increasing prominence within the maritime sector, serving as a critical link between safety governance, organisational learning, and crew protection. Fairness culture should not be misinterpreted as unconditional leniency; rather, it establishes clear boundaries between inadvertent human error, tolerable operational deviation, and reckless misconduct. By promoting non-punitive reporting, accountable behavior, and continuous feedback loops, a ship enhances its capacity to capture and assimilate risk information. In a high-stakes, hierarchical, and cross-cultural industry such as shipping, the value of fairness culture extends far beyond symbolic rhetoric. Its true worth lies in using concrete institutional mechanisms to reduce reporting anxiety, build trust, and ultimately convert near-miss data into preventive measures (Dekker, 2016).

Despite its evident importance, enforceable international rules supporting fairness culture remain limited and, in most cases, are virtually absent (Putra, et al., 2024). The industry currently lacks stable institutional backing for anti-retaliation protections, psychological safety, and internal non-punitive mechanisms following good-faith reporting (Carrera and Baumler, 2021). Moreover, the recent proliferation of digital reporting platforms adds further complexity. Mismatched data standards, the ambiguous legal status of electronic records, and algorithmic decisions that function as opaque black boxes collectively raise additional barriers to establishing a genuine fairness culture (Madsen and Kim, 2024). Thus, the difficulty in building such a culture is not merely a matter of unfamiliarity with the concept; rather, legal frameworks and governance mechanisms have yet to provide the necessary institutional backbone.

Driven by these concerns, this study examines the legal construction of maritime fairness culture. To identify the root causes, the study adopts semi-structured interviews rather than rigid surveys, engaging directly with maritime authorities, shipping managers, and frontline seafarers. The objective is to determine how these different groups perceive and navigate legal obstacles and digital governance challenges in their daily operations. Ultimately, this study seeks to answer several critical questions: What specific institutional gaps does fairness culture currently face? How do these gaps actively constrain near-miss reporting and organisational learning? And, most importantly, how can legal reform provide the institutional support that fairness culture requires?

2. Methodology

The adoption of a qualitative approach, specifically semi-structured interviews, was a highly deliberate methodological choice. The rationale can be summarized in three practical points. First, the core issues tackled here, the institutional grounding of fairness culture, the psychological barriers blocking near-miss reporting, and the deep trust deficits surrounding digital governance, are inherently complex (Flin, 2003). They involve subjective experiences, hidden motives, and highly personal perceptions of the rules, which a rigid, closed-ended survey simply cannot adequately capture. Second, semi-structured interviews give researchers the necessary flexibility to explore unexpected leads. While the interviewer works within a predefined framework, questions can be adaptively adjusted based on the participant's background and real-time responses. This iterative process allows the researcher to probe beneath surface narratives and uncover underlying mechanisms (Kvale, 2007). Third, the maritime domain is built on highly contextualized, practical knowledge. Interactive dialogue is the most effective means of capturing the nuanced, deck-level realities of maritime operations (Guest, et al., 2013). Qualitative interviews are therefore better suited to this task than quantitative surveys or static document analysis, as they reveal the discrepancies between formal regulations and their on-board interpretation. This capacity stems from the interactive nature of conversation, which captures the contextual realities of rule application at sea.

2.1 Participants and Sampling Strategy

To get a comprehensive understanding, this study utilized a stratified purposive sampling strategy (Guest, et al., 2020). The design deliberately targeted three key groups: frontline seafarers, shipping company managers, and maritime authorities.

When determining the sample size, the study followed the principle of theoretical saturation. Preliminary testing indicated that by the 18th seafarer interview, the emergence of new themes across three consecutive interviews consistently fell below 15%, signaling that data saturation had been reached. To account for potential information loss due to cross-cultural language translation, a 10% sample redundancy was incorporated. Ultimately, a total of 35 participants were successfully recruited, comprising 18 seafarers (ratings and junior officers), 10 shipping company managers (safety and operations), and 7 maritime authorities (inspectors and policy officers).

2.2 Question Design and Building Psychological Safety

To elicit candid and unmediated responses, the interview framework rested on two distinct strategies. First, researchers transformed abstract concepts into concrete, context-specific scenarios, deliberately avoiding leading questions and any form of moral judgment. Second, the interview protocol emphasised cultivating genuine rapport, with the objective of reducing participant defensiveness and encouraging uninhibited disclosure of genuine concerns.

Strategic questioning: The research team avoided questions such as "Do you agree with fairness culture?" or "Do you trust management?", as these tend to invite socially desirable answers. Instead, the dialogue was built around concrete behaviors (Lee, 1993).

Cultivating a safe space: Before each interview, ground rules were established. Participants were explicitly informed that the data would be used solely for academic purposes, anonymised, and never disclosed to shipowners. To address concerns about potential shadow penalties and retaliation, the interviewers often adopted a third-person framing (Lofland, et al., 2022). For example, they would ask: "Some crew members have mentioned … have you ever observed something similar?" This approach provided a psychological safeguard. Occasionally, an anonymised anecdote from a previous interview was shared to facilitate a more open exchange.

The reality of the responses: This calculated strategy proved effective in eliciting candid narratives. One seafarer described the hidden consequences of reporting a minor fuel pipe leak: the captain assigned the individual to three consecutive arduous night shifts, culminating in a performance review that cited inadequate initiative. This example illustrates a gap in anti-retaliation protection. Another sailor highlighted the cultural complexities of shipping: "In my culture, if a superior remains silent, it signals anger. After the system flagged me, the captain did not speak to me for three days. I immediately assumed I was in trouble and never reported a minor issue again." A chief engineer revealed the chilling effect of algorithmic governance. The system arbitrarily labeled him as "high-risk" due to frequent reporting; his supervisor merely advised him to "be careful next time" without explanation. Consequently, he ceased reporting minor issues, only reporting emergencies. These behavioral insights were captured solely because the seafarers perceived that they were not on trial.

2.3 Research Ethics and Quality Control

Ethics were not treated as a mere administrative formality. Prior to asking any questions, researchers briefed each participant on the study's objectives, data handling procedures, and the unconditional right to withdraw. During data processing, all names, corporate affiliations, and traceable details were systematically removed and anonymised.

To maintain strict data security, the core research team secured all audio files, transcripts, and coding materials. When directly quoting a participant, only their rank or essential contextual information was disclosed. Caution was exercised, as the aggregation of seemingly innocuous details could inadvertently reveal a participant's identity.

For quality control, the study relied on pilot testing of the interview framework, coding consistency checks, member validation, and rigorous data triangulation. These safeguards serve a fundamental purpose: mitigating researcher bias, enhancing interpretive stability, and ensuring that the findings accurately reflect the complex realities of maritime legal governance. Data analysis followed a thematic approach: after verbatim transcription, two researchers independently coded the interviews using Nvivo, identifying recurring themes through constant comparison; disagreements were resolved by discussion with a third researcher. Themes were then mapped against the research questions on legal protection, digital governance, and reporting behaviour.

3. Results Analysis

After analysing the interview transcripts and cross-examining them against existing policy documents, a clear pattern emerged. The legal foundation of maritime fairness culture is currently weakening along two main dimensions. The first is a lack of institutional support, evident in both mandatory regulations and daily corporate practice. The second concerns blind spots in the digital governance of near-misses, specifically regarding data standards, evidentiary value, and procedural safeguards. The following analysis explores how these two dimensions actively undermine safety.

3.1 The Institutional Void in Mandatory Regulations

Fairness culture is a frequently invoked concept in policy discourse, yet it lacks binding force in mandatory regulations and corporate frameworks. Several managers acknowledged that international rules function more as guidance or best-practice recommendations than as hard law. What specific non-punitive reporting obligations must a company assume? How can a whistleblower be shielded from retaliation? The rules do not provide clear, enforceable answers.

Cross-referencing policy texts confirms this gap. While current safety mandates require companies to establish reporting channels, they overlook the essential elements of a fairness culture, namely, non-punitive principles, robust protection mechanisms, and mandatory organisational feedback (Carrera and Baumler, 2021). Consequently, companies often treat their Safety Management Systems (SMS) as a compliance exercise, prioritising procedural adherence over genuine cultural safeguards. Many managers admitted that their internal

fairness policies remain frustratingly vague, failing to translate into actionable measures during audits, training, or daily performance reviews.

Thus, the primary obstacle facing the shipping industry is not a lack of conceptual awareness. The idea is widely recognized; it has simply not been codified into actionable, institutional mandates.

3.2 The Fragility of Good-Faith Reporting Rights

When the discussion turned to the personal consequences of reporting a near-miss, a pervasive fear of "invisible retaliation" emerged. Indeed, the lack of anti-retaliation protections dominated the conversations. Even when a seafarer avoids formal disciplinary action, they often face indirect penalties such as unfavorable shift assignments, denial of training opportunities, subtle negative adjustments in performance reviews, or unexplained delays in promotion. This form of covert retaliation may not resemble formal discipline on paper, but it effectively suppresses any willingness to report minor issues or emerging risks (Bhattacharya, 2011).

A closer examination of the legal framework explains why. While existing rules broadly condemn retaliatory behavior in principle, they fail to address critical questions: Who defines a "good-faith report"? How should an "invisible consequence" be legally characterised? And, crucially, who bears the burden of proof? The current framework remains silent on these issues. Consequently, a seafarer may have the theoretical right to report an incident, yet remain dangerously unprotected in practice.

Beyond general retaliation, the cross-cultural nature of modern shipping amplifies these vulnerabilities. Several foreign crew members noted that differing hierarchical values and communication styles mean that the same managerial response can be interpreted in vastly different ways. In the absence of structured cross-cultural communication protocols, seafarers may easily misread a manager's silence, evasive response, or an automated system flag as a veiled threat. Predictably, they withdraw, and the space for reporting shrinks further (Lu, et al., 2016).

3.3 Three Deficits in Digital Near-Miss Governance

Transitioning to the digital governance of near-misses, the analysis reveals three prominent institutional roadblocks: fragmented data standards, the evidentiary value of electronic reports and a lack of algorithmic due process.

(1) Fragmented data standards

Fragmented standards undermine the comparability and utility of incident data. Managers frequently noted that the same near-miss could be categorised differently depending on the flag state, corporate software, or reporting application. Under such conditions, it becomes difficult for a headquarters to accurately assess systemic risk or conduct cross-border comparisons. This indicates that while reporting has technically moved to digital platforms, the underlying logic and sharing protocols remain highly fragmented.

(2) Legal status of electronic reports

The uncertain evidentiary value of electronic reports fundamentally erodes trust in the system (Madsen and Kim, 2024). Multiple participants observed that digital logs, system screenshots, or mobile application records are rarely treated as formal and reliable evidence in practice. If it is uncertain whether a digital log will be accepted during an official investigation or liability dispute, crew members have little reason to trust the digital process. Deploying technology alone does not automatically improve governance; such tools remain virtually useless without an updated framework of evidentiary and procedural rules.

(3) Lack of algorithmic due process

The opacity of algorithms has created a new psychological barrier for crew members. Some seafarers stated that when a system classifies them as a "risk," they receive no explanation and have no channel to appeal or request a review. When the rationale behind a machine's decision is inaccessible and review processes are absent, crews instinctively perceive neutral technical alerts as organisational threats, thereby reducing their willingness to report future incidents.

Ultimately, the crisis in digital near-miss governance isn't about whether the software functions properly. The real issue is whether digital tools can operate reliably within a structured framework of unified standards, evidentiary acceptance, and procedural safeguards.

Taken together, these findings reveal a compounding problem: traditional legal gaps and digital governance flaws do not exist in isolation; they actively reinforce each other in practice. When the legal foundation of fairness culture is already weak, sailors naturally interpret ambiguous digital flags as potential threats. Conversely, when digital platforms operate without unified standards, legal recognition, or appeal mechanisms, any remaining trust among the crew deteriorates. This dynamic illustrates that translating fairness culture from theory into practice requires more than advocacy, it demands enforceable legal rules and reliable digital governance.

4. Discussion and Recommendations

4.1 Discussion

Why do these blind spots persist despite widespread conceptual awareness and technological capability? The root cause lies in the institutional architecture and historical biases of maritime governance. Fairness culture has long been confined to non-binding guidance, a direct consequence of the IMO's consensus-driven structure. Codifying fairness into binding law requires navigating a political landscape that balances seafarer rights, corporate autonomy, and flag-state sovereignty. Soft-law guidelines thus become an inevitable, pragmatic compromise.

At the corporate level, maritime safety governance has for decades prioritised technical compliance, focusing on hardware inspection, maintenance logging, and procedural requirements, while overlooking organisational silence, relational pressure, and the unspoken anxiety of junior officers. This hardware-centric path dependence was historically justifiable. Yet modern vessels have evolved into deeply integrated human-machine systems, in which human-factor risks become increasingly non-linear.

The cross-cultural composition of global crew members serves as a significant intensifying factor. A routine schedule change or generic system alert can elicit markedly different interpretations depending on cultural context. When legal frameworks fail to provide predictable protections, cultural anxieties emerge to fill the resulting uncertainty.

On the digital front, efficiency remains contingent upon institutional scaffolding. Non-harmonized data standards impede cross-border governance. Evidentiary rules have yet to align with technological advances. Furthermore, regulatory bodies lack the technical capacity to audit algorithmic code.

4.2 Recommendations

Operationalising fairness culture beyond theoretical discourse and embedding it in daily operations requires a decisive shift toward addressing specific institutional deficiencies.

First, regulatory authority should be strengthened through a "soft-law-first, gradual-hardening" strategy. Basic fairness provisions concerning non-punitive reporting and psychological safety obligations should initially be embedded into Port State Control procedures and industry guidelines, and subsequently incorporated into binding amendments of the ISM Code.

At the domestic level, a dedicated "Fairness Culture" chapter within maritime safety implementation regulations should explicitly delineate protective boundaries for good-faith reporting. It must ensure that near-miss reports cannot be used as negative performance evidence and that any form of covert retaliation is precluded.

Digital evidence protocols require active reform. Procedural law should be revised to grant encrypted, time-stamped electronic reports the same evidentiary weight as paper logs, accompanied by judicial interpretations guiding their admissibility in accident investigations.

Algorithmic systems should be subject to minimal procedural safeguards through outcome transparency rather than code transparency. Legislation should require algorithmic determinations to present clear visual justifications, while protecting core trade secrets. Accessible mechanisms for human review and appeal should be incorporated, operating within specified timeframes. Concurrently, regulators must develop competencies in algorithmic auditing.

This synchronised action across seafarers, corporate managers, and regulatory bodies can foster a virtuous cycle: empowered crew members report without apprehension, higher-quality data drives substantive improvement, and that improvement deepens cultural trust.

Only with such conditions will fairness culture transition from a theoretical aspiration into the operational reality of global shipping. The act of reporting must be legally protected. An electronic record must be deemed admissible in a tribunal. Algorithmic assessments must be governed by procedural law.

5. Conclusion

This study employed semi-structured interviews to identify persistent institutional weaknesses in the legal frameworks governing fairness culture, digital evidence, and algorithmic due process within the maritime sector. The findings indicate that, in the absence of clear regulatory safeguards, deeper technological integration may inadvertently intensify crew mistrust. Consequently, the legal institutionalisation of fairness culture and the digital transformation of shipping operations should proceed in a coordinated manner.

While these semi-structured interviews provided a rich, detailed understanding of maritime professionals' lived experiences, the findings remain inherently qualitative. A sample of 35 participants, though theoretically saturated, cannot fully capture the complexity of the global merchant fleet across all flag states and cultural contexts. Furthermore, digital technology evolves rapidly. The specific algorithmic challenges identified here represent a snapshot of the current era of opaque automated systems; by the time this paper reaches readers, digital reporting mechanisms will likely have evolved into more complex forms of automated governance.

Looking ahead, the prospects for maritime fairness culture remain promising. Maritime regulation now stands at a critical juncture where it must align with digital reality. Future research should more heavily incorporate human-in-the-loop designs, ensuring that automation of reporting systems does not inadvertently automate fear. Ultimately, the goal is to shift fairness culture from a top-down legal mandate to a bottom-up organisational habit. This is a long-term endeavor, but defining the legal foundations today is essential for navigating toward a truly safe and inclusive future for the global maritime workforce.

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Pathways to an environmentally sustainable cruise industry – what major cruise companies declare and whether it is enough

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Abstract: Using secondary data from corporate reports, websites, and other literature sources, this paper reviews the environmental sustainability policies, strategies, and reporting practices of the world's largest cruise company, Carnival Corporation. This is the first in a series of papers that will analyse the environmental sustainability policies, strategies, and reporting practices of major cruise companies and examine whether company efforts are measurable and effective or merely statements, and whether stronger partnerships with governments, academia, and local communities are needed to accelerate the green transition in cruise industry. The paper also highlights the complex interplay among industry regulations, standards, and practices, and emphasises the importance of transparent reporting of environmental performance indicators and open communication with all stakeholders. Numerous examples of good practice demonstrate that an industry once considered extremely negative for the environment and society can operate according to the principles of sustainability and cooperation among all stakeholders. Whether the cruise industry can be driven towards effective green transformation by relying on self-regulation and voluntary company-led sustainability efforts, or whether stricter legal regulation of the industry is necessary to facilitate transformation, remains open, highlighting the need for thorough, multifaceted analyses.

Keywords: cruise companies; sustainability; environmental performance; reporting; green transition

1. Introduction

Cruise tourism has grown steadily over the past 50 years and has become an important economic activity both globally and regionally, contributing to job creation, supporting local businesses, generating substantial revenue, and providing various socio-economic benefits (CLIA, 2025). The continuous increase in the number and size of cruise ships since the 1980s has exacerbated environmental and socio-economic problems related to high ecological footprints and mass tourism at destinations, negatively affecting ecosystems and the quality of life of local communities (Lloret et al., 2021; Hoarau-Heemstra et al., 2023; Papathanassis, 2023; Chou et al., 2024; Godovykh et al., 2025; Papathanassis, 2025). These negative environmental and socio-economic impacts depend on the carrying capacity of destinations (Notteboom et al., 2026), while the negative environmental impacts of cruise ships depend not only on carrying capacity and ecosystem characteristics, but also on the levels, characteristics and content of pollutants (USEPA, 2026). With rapid industry expansion, awareness of potential negative environmental and socio-economic impacts has increased among the public and within the cruise sector, supporting strong engagement from both the global public and the industry. Only 1% of the world's commercial fleet consists of cruise ships (CLIA, 2026), but they generally have a very negative public image. At the same time, given the complexity and severity of negative cruise industry impacts on ecosystems and society, the sustainability of cruising has become a significant issue in the industry, academia, and the public sphere. However, this has not led to stricter international regulations for cruise ships compared to other types of ships, but it has encouraged greater industry commitment to sustainability goals.

In addition to the legal framework regarding the environmental sustainability of the sector, which includes the International Convention for the Prevention of Pollution from Ships (MARPOL), the International Convention on the Control of Harmful Anti-fouling Systems on Ships (AFS), the International Convention for the Control and Management of Ships' Ballast Water and Sediments (BWM), and the Convention on Biological

Diversity (CBD), voluntary international environmental standards and reporting frameworks can greatly assist cruise companies in their efforts towards sustainability. Companies may align Environmental, Social and Governance ESG reporting with United Nations Sustainable Development Goals (SDGs) and targets, as well as a range of other ESG reporting standards, and environmental standards (Environmental management systems ISO 14001:2015, Eco-Management and Audit Scheme EMAS) (ICS, 2026). Global Sustainable Tourism Council (GSTC) Standards also address sustainable management and the socio-economic, cultural, and environmental impacts of the industry, while the voluntary certification programme for ships and ship management companies, Green Award, helps to exceed industry standards in safety, quality, and environmental performance (Green Award, 2026). Companies' commitment to sustainability can also be strengthened by robust stakeholder alliances at local, regional, and international levels. The most prominent stakeholder alliances include the Cruise Lines International Association (CLIA), the International Association of Ports and Harbors (IAPH), the International Association of Cities and Ports (AIVP) and its joint Cruises and Port Cities Working Group, the European Sea Ports Organisation (ESPO), the Association of Mediterranean Cruise Ports (MedCruise), other associations, and related initiatives.

To provide insight into the industry's commitment to sustainability goals, this paper reviews the sustainability policies and strategies of major cruise companies, as well as their sustainability reporting practices related to environmental sustainability, using secondary data from corporate reports, websites, and other literature sources. To address the limitations of a conference paper, the analysis focuses on the largest corporation, Carnival Corporation. This is the first in a series of papers that will analyse the sustainability policies, strategies, and reporting practices of major cruise companies in relation to environmental sustainability. The final aim is to determine whether corporate efforts are measurable and effective, or merely statements, and whether stricter legal regulation of the industry is necessary to facilitate the green transformation of the cruise sector.

2. Carnival Corporation's Sustainability Policies, Statements, Disclosures & Certifications

Carnival Corporation & PLC comprises distinct cruise lines and promotes itself as offering multiple ways to see the world – whether travelling in absolute luxury or simply letting your hair down and having fun – with over 90 ships delivering happiness. It is the leading cruise company, holding 40% of the global cruise market, with over 160,000 team members and 90 ships serving 13.5 million guests in 2024. The company consists of nine cruise lines, including: Carnival Cruise Line (family-friendly in North America, Australia, and Europe, with a 10.1% share of total industry revenue in 2025), Princess (premium experience, 6.2% share in 2025), P&O (5.5% share in 2025, UK), Aida (premium-quality, relaxing cruises for the German-speaking market, 4.1% share in 2025), Holland America (mid-sized ships and cultural programming, 3.5% share in 2025), Costa Cruises (Italian company, 3.4% share in 2025), Cunard (luxury cruising, 2.1% share in 2025, UK), and Seabourn (luxury small-ship cruising, 1.3% share in 2025) (Carnival Corporation Our Company, 2026). On its website, Carnival Corporation promotes Conscious Cruising From Ship To Shore as a commitment to people, communities, and the planet, aiming to set a standard of sustainability for the cruise industry. The company highlights five priorities: maintaining excellence in compliance, environmental protection, and the safety, health, and well-being of every life touched; and leading with the industry’s smartest solutions that deliver on the sustainability roadmap to 2030. Six core values are listed: Listen & Learn; Speak Up; Respect & Protect; Always Improving; Better Together; and Guest Obsessed. These values underpin the company’s sustainability policy and strategies and are well aligned with the Sustainable Development Goals. The company also declares its commitment to shareholder-centred policies and practices, and sound principles of corporate governance (Carnival Corporation Our Company, 2026).

The company website, in the section Sustainability, From Ship to Shore: Our Impact, addresses three main issues: sustainability, community relations, and good health, inclusion, and belonging. The Sustainability section outlines the mission and vision: Leading By Example: Our Path, Our Promise. Carnival Corporation’s sustainability goals were first outlined in 2015, then updated in 2018 and most recently in 2020. The company affirms its commitment to minimising its environmental footprint, focusing on achieving net zero and climate action, and aims to serve as an example of environmental excellence globally. In addition to statements on priorities, values, mission, and vision, the section provides the history of Sustainability Reports from 2010 to 2025, which will be discussed later (Carnival Corporation Sustainability Reports, 2026).

A dedicated subsection within the Sustainability section focuses on Advanced Air Quality Systems, highlighting that Carnival Corporation operates 10 LNG-enabled cruise ships and has six more on order, while 70% of the fleet can use shoreside electric power. It explains the Advanced Air Quality System (AAQS), or scrubber, and notes that all systems use continuous monitoring equipment to automatically record all required parameters, but does not discuss the disadvantages of using scrubbers. Scrubber wash water is continuously measured and recorded for pH, turbidity, and polycyclic aromatic hydrocarbons (PAH) after the tower and before discharge, with records kept on board for 18 months in accordance with IMO MEPC guidelines. Furthermore, the webpage provides insight into a two-year study that analysed 281 scrubber wash water samples from 53 Carnival Corporation ships. Independent laboratories accredited by the International Organization for Standardization (ISO) tested the samples for 54 parameters using standardised US Environmental Protection Agency (EPA) methods, while DNV GL reviewed the laboratory test data and concluded that they meet industry benchmarks.

The Sustainability subsection Policies, Statements, Disclosures & Certifications includes several key documents related to environmental sustainability, such as the Health, Environmental, Safety, Security and Sustainability Corporate (HESS) Policy, Transparency in Supply Chains Statement, Task Force on Climate-Related Financial Disclosures (TCFD), Sustainability Accounting Standards Board (SASB) Cruise Line Standard disclosures and ISO 14001:2015 certification. The HESS Policy outlines clear measures for implementation in the management of Carnival Corporation and its cruise line: Identifying employees responsible for HESS and sustainability performance and ensuring clear lines of accountability; Developing and implementing policies, procedures, and training programmes to support HESS and sustainability commitments; Identifying, assessing, monitoring, and managing HESS and sustainability risks and opportunities; Providing HESS and sustainability support, training, advice, and information, as appropriate, to guests, employees, and others working on behalf of the company; Leveraging HESS audit and investigation findings and event causes to identify and implement corrective and preventive actions to avoid recurrence; Promoting the practice of speaking up when there is a concern, and maintaining a reporting hotline that allows for anonymous reporting of HESS, ethics, and compliance concerns; Promoting industry best practices, publicly reporting to, and maintaining open dialogue and cooperation with, stakeholders on HESS and sustainability matters; Conducting a corporate senior management review of this policy at least annually. The Transparency in Supply Chains Statement categorises, manages, and reports on climate risks and opportunities using qualitative and quantitative scenario analyses to evaluate potential short-, medium-, and long-term impacts on the business. It discloses, among other matters, structure, business model, supply chain, risk assessment and management, effectiveness and performance indicators, and governance and stakeholder engagement. TCFD complies with the requirements of the UK Companies Act 2006 and the TCFD's four pillars: Governance, Strategy, Risk Management, and Metrics and Targets (Table 1). It lists five 2030 Climate Action Goals: achieve a 20% reduction in GHG intensity relative to the 2019 baseline, measured in both grams of CO2e per ALB-km and kilograms of CO2e per ALBD by 2026; achieve 75% fleet shore power connection capability by 2028 and 80% by 2030; expand LNG ships to more than 25% of fleet capacity from 2030 to 2033; expand battery and biofuel capabilities; and continue to measure Scope 3 emissions.

Table 1. Four TCFD pillars: Governance, Strategy, Risk Management and Metrics and Targets (Carnival Corporation Task Force on Climate-Related Financial Disclosures, 2026.).

TCFD Pillar	Recommended disclosures
Governance	Boards' oversight of climate-related risks and opportunities.
	Management's role in assessing and managing climate-related risks and opportunities.
Strategy	The climate-related risks and opportunities the organisation has identified over the short, medium, and long term.
	The impact of climate-related risks and opportunities on the organisation's businesses, strategy, and financial planning.
	The resilience of the organisation's strategy, taking into consideration different climate-related scenarios, including a 2°C or lower scenario.
Risk Management	The organisation's processes for identifying and assessing climate-related risks.
	The organisation's processes for managing climate-related risks.
	Integration of processes for identifying, assessing, and managing climate-related risks into the organisation's overall risk management.
Metrics and Targets	The metrics used by the organisation to assess climate-related risks and opportunities in line with its strategy and risk management process.
	Scope 1, Scope 2, and Scope 3 Greenhouse Gas (GHG) emissions, and the related risks (1.5°C Scenario; 2.8°C Scenario and 4°C Scenario).
	The targets used by the organisation to manage climate-related risks and opportunities and performance against targets.

Carnival Corporation is certified by ISO 14001:2015 and the SASB Standard, an essential tool for companies to make comparable sustainability disclosures (IFRS S1 General Requirements for Disclosure of Sustainability-related Financial Information and IFRS S2 Climate-related Disclosures), revealing sustainability-related risks and opportunities relevant to investors and the general public (Table 2).

Table 2. Carnival Corporation SASB Index (Carnival Corporation SASB Index, 2026).

Topic	Code	Accounting metric
Greenhouse Gas Emissions	TR-CL-110a.1	Gross global Scope 1 emissions – Metric Tonnes Carbon Dioxide Equivalent
	TR-CL-110a.2	Discussion of long-term and short-term strategy or plan to manage Scope 1 emissions, emissions reduction targets, and an analysis of performance against those targets
	TR-CL-110a.3 (1)	(1) Total energy consumed – Gigajoules (GJ) (2) percentage heavy fuel oil (3) percentage onshore power supply (OPS) (4) percentage renewable
	TR-CL-110a.4	Average Energy Efficiency Design Index (EEDI) for new ships
Air quality	TR-CL-120a.1	Air emissions of the following pollutants: (1) NOx (excluding N2O), (2) SOx, and (3) particulate matter (PM10)
Discharge Management and Ecological Impacts	TR-CL-160a.1	Total amount of ship waste discharged to the environment; percentage treated prior to discharge
	TR-CL-160a.2	Percentage of fleet implementing (1) ballast water exchange and (2) treatment
	TR-CL-160a.4	Number of notices of violations received for dumping

Carnival Corporation began its Environmental Management System (EMS) initiative in 2005 and, in 2006, certified all Operating Lines and ships to the ISO 14001 EMS standard. The corporation has developed a GHG Inventory Management Plan (GHG IMP) in accordance with the requirements of ISO 14064-1:2006 and the Greenhouse Gas Protocol, which includes the policies, procedures, and other management system elements for developing, collecting, calculating, verifying, managing, and reporting Carnival's GHG inventory and emissions.

3. Carnival Corporation's Sustainability Reports – Environmental performance

Since 2008, the Corporation has publicly disclosed the environmental, social, and governance performance of its Operating Lines, using the internationally recognised Global Reporting Initiative (GRI) framework. In 2010, the Operating Lines Sustainability Reports were published, expanding on the annual public Environmental Management Reports first issued in 2006. Carnival included all sustainability-related issues identified through stakeholder engagement and analysed them using a prioritisation matrix. This enabled the Corporation to identify the issues reported and measured internally, select a core set of issues and a related metrics reporting framework and process, decide the content for each metric, and determine the approach to reporting and the use of metrics data for other purposes. The first Corporate Sustainability Report from 2010 was published in accordance with the G3 Sustainability Reporting Guidelines of the GRI and included sustainability performance data based on information supplied by its Operating Lines, including quantitative and qualitative data collected, aggregated, and analysed using the Corporation's in-house data collection and reporting systems and industry sources, aligning data gathering with the GRI indicator protocols. The 2010 Sustainability Report included the Profile disclosures, Management approach disclosures, Performance indicators and sector supplement performance indicators, and also provided detailed information on data measurement and calculation approaches for each of 34 selected economic, environmental (Table 3), and social performance indicators, along with the associated tables and graphs.

Table 3. Environmental Performance Indicators included in Sustainability Reports 2010.

Resource use (energy, water, biodiversity)	GHG, ODS and air pollutants	Management, mitigation and compliance
Direct Energy Use (EN3): EN 3.1 – Direct Energy Consumption by Users (Ship and Shore) and Total Energy Consumption Rate EN 3.2 – Total Ship Fuel Consumption and Ship Fuel Consumption Rate	Direct and Indirect Greenhouse Gas Emissions (EN16): EN 16.1 – Direct and Indirect Greenhouse Gas (GHG) Emissions by Weight EN 16.2 – Direct Greenhouse Gas (GHG) Emissions by Weight (Ship and Shore) EN 16.3 – Ship Direct Greenhouse Gas (GHG) Emissions by Weight EN 16.4 – Indirect Greenhouse Gas (GHG) Emissions by Weight (Shore and Ship)	Shipboard Waste Management (EN22): EN 22.1 – Total Weight of Waste by Type and Disposal Method EN 22.2 – Hazardous and Non-Hazardous Waste and Total Waste Rate EN 22.3 - Non-Hazardous and Hazardous Waste Recycled

Indirect Energy Use (EN4): EN 4.1 – Indirect Energy Consumption by Users (Shore and Ship)	Greenhouse Gas (GHG) Reductions (EN18): EN 18.1 – Total Ship Fuel Greenhouse Gas (GHG) Emissions and Ship Fuel GHG Emission Rate	Significant Spills (EN23): EN 23.1 – Total Number and Volume of Reportable Spills
Energy Savings Initiatives and Results (EN6)	Ozone-Depleting Substances (EN19): EN 19.1- Ship Fugitive Refrigerant Releases and Emissions of Ozone Depleting Substances by Weight	Environmental Impact Mitigation (EN26)
Water Consumption (EN8): EN 8.1 – Water Withdrawal by Source and Water Consumption Rate	NOx, SOx and Other Significant Air Emissions (EN20): EN 20.1 – Total Sulphur Oxides (SOx) Emissions by Weight and SOx Emission Rate EN 20.2 – Ship Fuel Breakdown by Type in Percent of Total Fuel EN 20.3 – Total Nitrogen Oxides (NOx) Emissions by Weight and NOx Emission Rate EN 20.4 – Total Particulate Matter (PM2.5) Emissions by Weight and PM2.5 Emission Rate	Environmental Compliance (EN28): EN 28.1 – Monetary Value of Fines and Total Number of Non-Monetary Sanctions for Non-Compliance with Environmental Laws and Regulations
Biodiversity – Habitats Protected/Restored (EN13)	Shipboard Wastewater Management (EN21): EN 21.1 – Bilge Water Discharged to Sea and Bilge Water Sea Discharge Rate EN 21.2 – Gray Water Discharged by Destination and Gray Water Discharge Rate EN 21.3 – Black Water Discharged by Destination and Total Black Water Discharge Rate EN 21.4 – Biomass/Sewage Sludge Discharged by Destination and Discharge Rate	

To reflect new Global Warming Potentials published in scientific and guidance documents after 2008, Carnival updated several GHG emission factors, including those used to calculate normalised intensity metrics, as well as electricity and steam emission factors, to enable more meaningful data comparisons. LRQA Americas Sustainability, Inc. (LRQA) verified Carnival's GHG inventories in accordance with ISO 14064-3:2006, Greenhouse gases – Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions, in conformance with ISO 14064-1:2006, Greenhouse gases – Part 1: Specification with guidance at the organisation level for quantification and reporting of greenhouse gas emissions and removals. The Corporation aligned its work of organisations and incentives including Cruise Lines International Association (CLIA), International Chamber of Shipping (ICS), European Community Shipowners' Associations (ECSA). Ship Emission Abatement and Trading (SEAaT), Global Environmental Management Initiative (GEMI), Sustainable Shipping Initiative (SSI) and many others. The sustainability reports have maintained a consistent approach over the years, providing data on Strategy and Analysis; Governance, Commitments and Engagement; Management Approach and Declaration of the GRI; and external assurance, including the Carnival Corporation GRI Index and a performance summary. Since 2021, the SASB Index: Cruise Line Standard has been included in the sustainability report. Table 4 presents data on environmental performance indicators for the fiscal years 2010, 2015, 2020, and 2024.

Table 4. Performance summary: Environmental performance indicator data for fiscal years 2010, 2015, 2020, and 2024. (authors according to: Carnival Corporation Sustainability reports, 2026).

Performance data (units)	2010	2015	2020	2024
Greenhouse gas emissions (GHGS) (EN 16, EN 18)				
Total GHG Emissions - Location Based (MT CO_2e)/(scope 1 & 2)*	10,748,636	10,374,922	6,296,960*	9,714,000
Total GHG Emissions - Market Based (MT CO_2e)/(scope 1 & 2)*	-	10,377,235	6,298,244*	-
Direct GHG Emissions (MT CO_2e)/Scope 1*	10,700,266	10,320,701	6,268,752*	9,680,000*
Ship Direct GHG Emissions (MT CO_2e)	10,677,839	10,301,296	6,259,645	-
Ship Fuel GHG Emissions (MT CO_2e)	10,447,851	10,059,618	6,121,898	-
Ship Refrigerant GHG Emissions (MT CO_2e)	229,988	241,678	137,747	-
Shore Direct GHG Emissions (MT CO_2e)	22,428	19,405	9,107	-
Indirect GHG Emissions - Location Based (MT CO_2e)/Scope 2*	48,370	54,221	28,208*	34,000*
Shore Indirect GHG Emissions - Location Based (MT CO_2e)	44,591	45,201	24,480	-
Ship Indirect GHG Emissions - Location Based (MT CO_2e)	3,779	9,020	3,727	-
Indirect GHG Emissions - Market Based (MT CO_2e) /Scope 2*	-	56,533	29,492*	49,000*
Shore Indirect GHG Emissions - Market Based (MT CO_2e)	-	44,646	24,341	-
Ship Indirect GHG Emissions - Market Based (MT CO_2e)	-	11,887	5,151	-
Ship Fuel GHG Emission Rate (Grams CO_2e/ALB-Km)	303	266	298	-
Scope 3 Indirect GHG emissions (MT CO_2e)	-	-	-	8,671,000
GHG emissions Intensity (kg CO_2e/ALBD)	-	-	-	100
GHG Emissions Intensity Reduction from 2008 (g CO_2e/ALB-Km)	-	-	-	203
Ozone-depleting emissions (EN 19)				
Ship Fugitive Refrigerant Releases (kg)	124,376	125,603	74,384	-
Ship Ozone Depleting Substances (ODS) Emissions (kg CFC-11e)	1,975	2,130	200	-

NOx, SOx and particulate matter (EN 20)				
Total SOx Emissions (MT)	140,218	151,157	5,728	9,000
SOx Emissions Rate (kg SOx/NM)	15.2	16.4	1.2	-
Total NOx Emissions (MT)	215,719	206,778	114,301	161,000
NOx Emissions Rate (kg NOx/NM)	23.4	22.4	24.7	-
Total Particulate Matter (PM2.5) Emissions (MT)	3,983	3,817	3,817	6,000
Particulate Matter (PM2.5) Emission Rate (kg PM/NM)	0.43	0.41	0.83	-
Advanced Air Quality System Fleet Coverage	-	-	-	95%
Energy and electricity (EN 3, EN 4)				
Scope 1 - Direct (Energy Production from Fuel) (MWh)	-	-	-	34,195,000
Total Energy Consumption/Scope 1 - Total Direct Energy Consumption* (Gigajoules)	136,071,929	131,964,513	80,876,978*	-
Ship Energy Consumption/Ship Direct Energy Consumption* (Gigajoules)	135,785,273	131,697,157	80,746,966*	-
Shore Energy Consumption/Shore Direct Energy Consumption* (Gigajoules)	286,656	267,356	130,012*	-
Total Energy Consumption Rate/Total Direct Energy Consumption Rate* (Kilojoules/ALB-Km)	3,948	3,492	3,936*	-
Total Ship Fuel Consumption (MT)	3,318,750	3,181,202	1,915,261	-
Ship Fuel Consumption Rate (g Fuel/ALB-Km)	96	84	93	-
Total Purchased Electricity/Scope 2* (MWh)	70,439	115,819	65,399	-
Scope 2 - Indirect (Purchased Electricity) (MWh)	-	-	-	120,000
Shore Purchased Electricity (MWh)	64,021	85,925	52,814	-
Ship Purchased Electricity (MWh)	6,418	29,894	12,585	-
Ship fuel (EN 20)				
High Sulphur Fuel Oil (HSFO)	87.1%	78.4%	58.9%	-
Low Sulphur Fuel Oil (LSFO)	8.0%	1.3%	1.3%	-
Marine Diesel Oil/Marine Gas Oil (MDO/MGO)	4.9%	20.2%	38.7%	-
Liquefied Natural Gas (LNG)/ LNG-capable Fleet Coverage*	-	-	1.14%	18.6%*
Water (EN 8, EN 21)				
Total Water Consumption (MT)	23,626,059	25,591,974	11,082,731	25,845,000
Water Purchased (From Shore) (MT)	6,375,849	6,099,369	1,868,880	-
Water Produced (From Sea) (MT)/Percentage*	17,250,210	19,492,605	9,213,851	88.6%*
Water Consumption Rate (Litres/Person-Day)	237	232	251	194
Bilge Water Discharge to Sea (MT)	244,609	223,185	99,328	93,000
Bilge Water Sea Discharge Rate (Litres/NM)	26.5	24.2	21.5	-
Total Gray Water Discharged (MT)	16,280,438	17,494,817	-	-
Gray Water Discharged to Sea (MT)	16,115,456	17,347,118	6,823,474	14,378,000
Gray Water Discharged to Shore (MT)	164,982	147,698	-	-
Gray Water Discharge Rate/Sea Discharge Rate (Litres/Person-Day)	163	159	155.1*	107.7*
Total Black Water Discharged (MT)	7,075,801	7,692,427	-	-
Treated Black Water Discharged to Sea (MT)	6,995,178	7,578,235	4,022,293	10,934,000
Treated Black Water Discharged to Shore (MT)	54,875	44,721	-	-
Untreated Black Water Discharged to Sea (MT)	16,138	69,303	-	-
Untreated Black Water Discharged to Shore (MT)	9,610	169	-	-
Black Water Discharge Rate/ Sea Discharge Rate* (Litres/Person-Day)	71.0	69.8	91.4*	81.9*
Percentage of Fleet Capacity with Advanced Waste Water Treatment Systems	-	-	-	74%
Total Biomass/Sewage Sludge Discharged (MT)	291,040	-	-	-
Biomass/Sewage Sludge Discharged to Sea (MT)	289,855	-	-	-
Biomass/Sewage Sludge Discharged to Shore (MT)	1,185	-	-	-
Total Biomass/Sewage Sludge Discharge Rate (Litres/Person-Day)	2.92	-	-	-
Waste disposal (EN 22)				
Total Waste (MT)	489,075	486,451	195,773	289,000
Hazardous Waste (MT)	25,463	27,904	88,897	102,000
Non-Hazardous Waste (MT)	463,612	458,546	106,875	186,000
Total Waste Rate*/Waste Rate (Excluding Recycling) (Kilograms/Person-Day)	4.9*	3.2	3.0	1.5
Total Waste Disposed to Shore (MT)	141461	160,748	-	-
Hazardous Waste Disposed to Shore (MT)	6,394	11,308	-	-
Non-Hazardous Waste Disposed to Shore (MT)	135,067	149,440	-	-
Total Waste Recycled to Shore (MT)	127018	129,499		86,000
Hazardous Waste Recycled to Shore (MT)	17,919	15,648	-	-
Non-Hazardous Waste Recycled to Shore (MT)	109,099	113,851	-	-
Non-Hazardous Waste*/Food waste Discharged to Sea (MT)	123,760*	105,658	-	-
Non-Hazardous Waste*/Total waste Incinerated Shipboard (MT)	96,836*	90,545	-	-
Non-Hazardous and Hazardous Waste Recycled	26.0%	26.6%	27.3%	-
Spills and fines (EN 22, EN 23, EN 28)				
Total Number of Significant Spills	0	0	-	-
Total Number of Reportable Spills	26	49	-	-
Total Volume of Reportable Spills (Litres)	984	8,488	-	-
Total Number of Non-Monetary Sanctions	0	0	-	-
Monetary Value of Fines ($)	0	35,900	-	-

Since 2022, the corporation has included Scope 3 emissions in its sustainability reports. Notably, the corporation's 2024 direct (Scope 1) GHG emissions are largely generated by ships, accounting for over 99% of total Scope 1 and Scope 2 emissions. For Scope 3, the corporation conducted a baseline inventory of its 2019 emissions in 2022, following the Greenhouse Gas Protocol and ISO 14064-1:2018 guidelines. The corporation calculated its 2024 Scope 3 emissions (estimated at 47% of the corporation total GHG emissions) despite the absence of universal standards for Scope 3 estimation. Scope 3 emissions estimates rely on data from other organisations and various emission factor databases, and are subject to uncertainties. As the corporation notes, frequent changes in emission factors present challenges in tracking and measuring value chain-related emissions, and standardisation of emission factors would greatly assist companies in evaluating their emissions. Notably, data on spills and fines (EN 22, EN 23, EN 28), including the total number of significant spills, total number of reportable spills, total volume of reportable spills (litres), total number of non-monetary sanctions, and monetary value of fines ($), have not been disclosed since 2018. It is also evident that the number of disclosed environmental performance indicators has declined since 2020. However, the company’s commitment and the availability of a reporting standard, in this case the GRI, have enabled the consistent disclosure of environmental performance indicators since 2008, which greatly contributes to the transparency of environmental data important to scientists and the general public. Nevertheless, this good practice does not diminish the necessity for monitoring, collection, aggregation, and analysis of environmental performance, possible strict regulation for certain environmental issues, and ongoing engagement of scientists, decision-makers, and local communities.

4. Carnival Corporation's examples of good practice: Less Left Over and Every Drop Counts strategies

Carnival Corporation highlights numerous examples of good practices and campaigns, including Less Left Over and Every Drop Counts. To responsibly feed over 13 million passengers each year, the corporation has integrated sustainable practices throughout its Less Left-Over strategy, which includes initiatives such as Optimising Every Delicious Bite, From Surplus to Solutions, and Responsibly Manage the Rest. The aim is to reduce food waste by 50% by 2030, and by the end of the 2024 fiscal year, it has reduced food waste by 44% system-wide. The From Surplus to Solutions initiative aims to eliminate food waste by donating surplus ingredients and meals to registered food banks or repurposing food scraps for uses such as farm-ready organic compost, ingredients for upcycled goods, and biofuel production. The Responsibly Manage the Rest initiative seeks to naturally break down, condense, and sustainably dispose of unused food. Every Drop Counts strategy aims to use less and reclaim more resources. The corporation's water use rate is 51 gallons per person per day, 38% less than the US national average of 82 gallons per person per day, achieved by using water-smart appliances such as efficient laundry machines, dishwashers, and performance flow showerheads and sink aerators. The corporation also sources 88% of the freshwater used on board through desalination. All ships in the fleet are equipped with wastewater sanitation devices, while 75% of fleet capacity is equipped with Advanced Waste Water Treatment Systems to purify the water used on board to municipal water quality. These initiatives are examples of well-organised and well-coordinated campaigns that include important industry stakeholders, from corporation employees to value-chain partners to final users of the service, giving them a sense of purpose in supporting the environment and highlighting the role of education in the green transition.

5. Conclusion

Carnival Corporation is the leading cruise company, comprising nine cruise lines and holding 40% of the global cruise market. The company’s objectives are closely aligned with the Sustainable Development Goals, which underpin Carnival Corporation’s policies, strategies, and incentives, including the HESS Policy, the Transparency in Supply Chains Statement, and the TCFD. The corporation certified all operating lines and ships to the ISO 14001 EMS standard and has developed a GHG Inventory Management Plan (GHG IMP) in accordance with the requirements of ISO 14064-1:2006. Since 2008, the corporation has publicly disclosed the environmental performance of its operating lines using the GRI framework. Sustainability reports have maintained a consistent approach over the years. As frequent changes in emission factors have made tracking and measuring value chain-related emissions challenging, standardisation of emission factors would greatly assist companies in evaluating their emissions. Notably, the number of disclosed environmental performance indicators has declined since 2020, including data on spills and fines, which have not been disclosed since 2018. While this paper does not try to diminish the importance of a reporting standard such as the GRI in enabling consistent disclosure of environmental performance indicators that contribute to the transparency of the cruise

business, there is considerable room for improvement in the monitoring, collection, analysis, and interpretation of environmental performance indicators. This paper is the first in a series reviewing the environmental performances of major cruise companies and represents an initial step in investigating the real impact of cruise companies on the environment and human health. The question of whether current regulations are strict enough, especially when relying on self-regulation and voluntary company-driven sustainability efforts, or whether more needs to be done, remains open, and further thorough analyses are needed.

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A Simulation-Based Training Curriculum Design for Port Radio Operators in Japan

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Abstract: Vessel Traffic Services (VTS) support navigational safety and port efficiency through technologies, standardised communication protocols, and highly trained human operators. Japan operates a mature VTS system across high-density waterways and major ports, within which Port Radio Operators (PROs) carry a significant share of shore-to-ship voice communications as vessels enter and exit its port network. Despite their importance to VTS operations throughout the world, PROs are underserved in international VTS training frameworks, which tend to focus mostly on VTS Operators and VTS Supervisors. Drawing on over ten years of experience delivering PRO training to Japan's major port radio services, this paper proposes a simulation-based training curriculum for PRO development modelled on the training currently being implemented in Japan. The curriculum is presented as a design proposal that can be adapted to accommodate regional variances, not a strictly deployed programme. The training system is built around AIS-display-driven scenarios that cover various situations including grounding, medical emergencies, not-under-command vessels, traffic lane violations, and non-compliance conditions drawn from documented operational incidents that have occurred at Japanese ports and high-traffic waterways. The paper proposes a rubric with three dimensions and four-level descriptors, and identifies validation work required to move the framework from design to deployment.

Keywords: VTS; simulation-based training; port radio operations; maritime English; IALA V-103

1. Introduction

Port Radio Operators (PROs) manage the frontline of shore-to-ship voice communication in Japan's VTS network. International VTS training frameworks have developed most fully around VTS Operators (VTSOs) and Supervisors, leaving PROs comparatively underserved despite their crucial role in operational communications.

VTS is defined by the International Maritime Organization (IMO) under SOLAS Regulation V/12 as a shore-based service implemented in areas where traffic density and/or navigational risk justifies it (IMO, 2025). Within the VTS framework, PROs have distinct roles from VTSOs and VTS Supervisors. VTSOs oversee traffic management authority and supervisors hold strategic oversight, while the PRO's role centres on communication management. This communication mostly entails monitoring and responding to VHF channels using Standard Marine Communication Phrases (SMCP) and coordinating between vessels and port authorities in real time. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) V-103 model course series provides harmonised competency frameworks across VTS personnel tiers, but accredited provision is more fully developed for VTSOs and Supervisors than for PROs (IALA, 2024).

That gap matters because radio communication has a high risk for error in multilingual settings where English SMCP functions as a professional lingua franca (Bocanegra-Valle, 2011). For L2 English users like most of Japan's PRO workforce, producing standardised phraseology accurately is a real operational challenge. Uchida and Sugimoto (2023) found a mean intelligibility rate of 45.8% for maritime English terms pronounced by Japanese deck cadets, and corpus analysis of authentic routine ship–shore exchanges shows real communication departing substantially from standard protocol on both ship and shore sides (Jurkovič, 2022). Simulation-based training (SBT), endorsed by IALA as the principal method for VTS competency development and assessment (IALA, 2022), offers a way to practise these demands in a controlled setting. VTS-specific

simulation studies further show measurable gains in operators' anticipation of developing situations (Song, Itoh and Kawamura, 2022).

The IALA V-103/1 competency framework applies across regions, but its value depends on scenario content that reflects what PROs actually encounter in a given local setting. The curriculum proposed here is grounded in Japan's operational context and draws on two practitioner sources. The first source is the author's ongoing work delivering training to operators at Japan's major port radio services, which consist of the PRO population that is this paper's focus. The second source is applied linguistics research in maritime English conducted at Kobe University Graduate School of Maritime Sciences, including prior work on assessment instrument design for cross-cultural maritime competencies (Rooks, Progoulaki and Szwed, 2015) and on SMCP usage in VHF communications at Japanese VTS centres (Rooks, 2023). Throughout this paper, "VTS operator training" refers in the broad sense to training personnel within the VTS system rather than the narrower VTSO role defined above. This paper proposes a pilotable curriculum framework assessed against V-103/1 competency standards.

This paper aims to make three contributions to this research field. The first is to provide a clearly defined distinction of PROs within the VTS role framework as human resources whose communication-centred competency profile is underrepresented in international training frameworks. The second contribution is to present a transferable simulation-based curriculum for VTS operator training that consists of five operationally grounded scenario categories and a three-dimensional, four-level assessment rubric mapped to IALA V-103/1 competencies. The third and final contribution is to outline the validation programme required to move the framework from design toward evidence-based deployment.

2. VTS in Japan and the PRO Role

Japan operates seven VTS centres managed by the Japan Coast Guard (JCG) under the Ministry of Land, Infrastructure, Transport and Tourism (MLIT): Tokyo Wan, Ise Wan, Nagoya-Ko, Osaka Wan, Bisan Seto, Kurushima Kaikyo, and Kanmon Kaikyo. Each centre utilises radar, AIS (Automatic Identification System), VHF radio, and CCTV/ITV for monitoring traffic in real time (Japan Coast Guard, 2024). Tokyo Maritime Traffic and Information Service (MARTIS) and Osaka MARTIS provide a good indicator of the operational range of PRO training: high-density traffic routes through designated areas, dual-language communications, dealing with very large vessels and dangerous goods carriers, and responding to fishing-vessel incursions into designated lanes in the Akashi Strait (Japan Coast Guard, 2024; Tokyo Wan Vessel Traffic Service Center, 2023).

In Japan, the Ministry of Internal Affairs and Communications (MIC) oversees maritime radiotelephone and radar operation licensing. To meet licensing requirements, PRO competence is measured across five areas (MIC, 2025). The most technically specific is SMCP proficiency, which is the accurate use of IMO Standard Marine Communication Phrases (and their subset of message markers), especially in safety-critical exchanges that require English (IMO, 2001). Layered on top of the SMCPs is knowledge of local procedures like port-specific reporting schemes, traffic routes, and pre-entry protocols. Sensor competency involves reading AIS/radar in relation to synthesizing ongoing voice traffic. All of these aspects are supported by chart and ECDIS awareness (IALA, 2022). A crucial aspect of PRO responsibilities is handling emergency procedures such as distress, urgency, and safety communications including GMDSS (Global Maritime Distress and Safety System) and MRCC (Maritime Rescue Coordination Centre) coordination (IMO, 2024a; IMO, 2024b). Underlying these dynamics are human factors, specifically communicating clearly through workload bursts, shift handovers, and inter-agency coordination. Workload in Japanese shore-side traffic operations has been studied for PROs directly. Kitamura et al. (2017) used salivary $NO3^-$ as a physiological marker across operating conditions, noting changes in stress levels of PROs across various times and types of interactions, although different role terminology was used for PROs in the paper. Sharma et al. (2026) conducted a systematic review of two decades of VTS research that similarly identifies workload, situation awareness, decision-making, and communication as the dominant human-factor elements of operator performance.

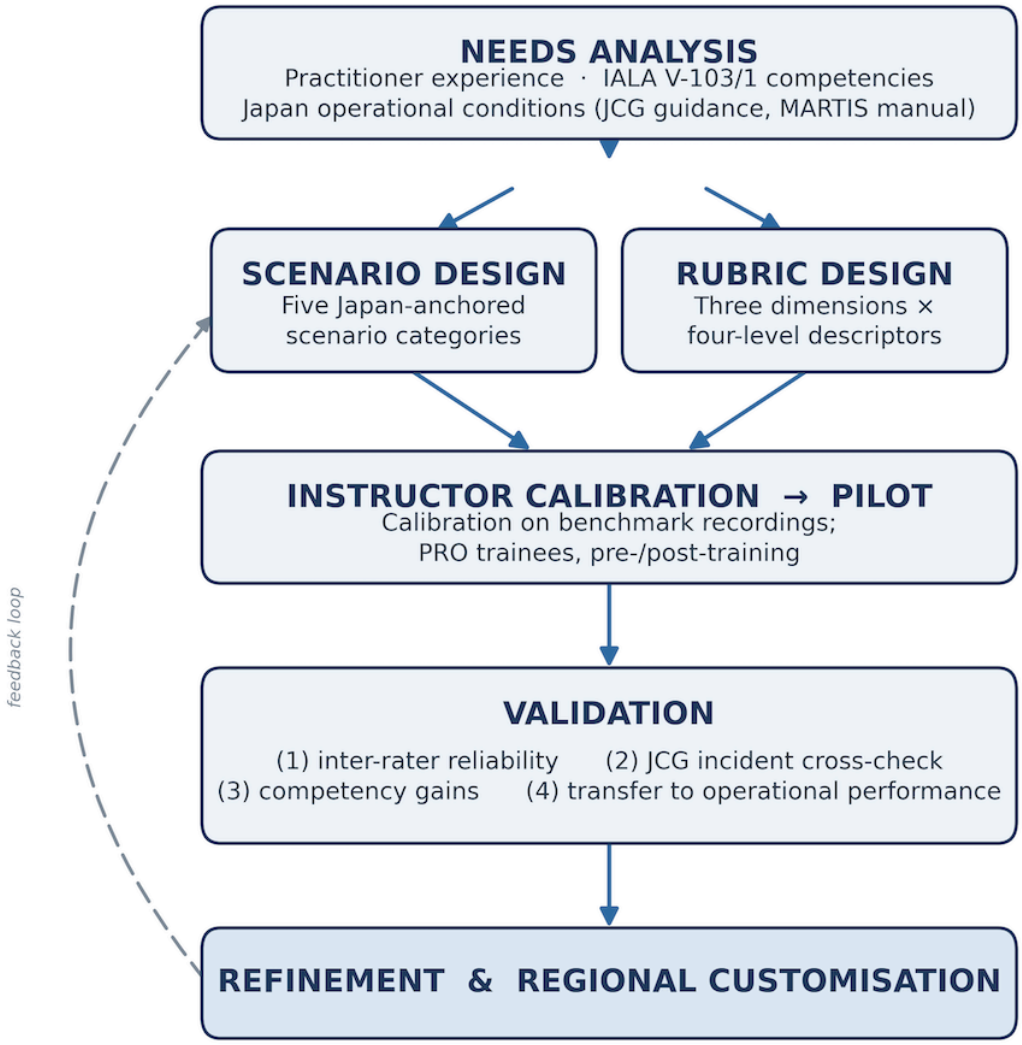
The true indicator of the skill level required by the PRO competencies listed above is that they aren’t performed one at a time; they must work in parallel. A typical stretch of work for a PRO may entail observing

AIS, producing an SMCP advisory, switching languages for a routine exchange, and maintaining procedural continuity, all within the same brief operating window. The integration of these skills is what the curriculum below is designed to develop.

3. Simulation-Based Training Curriculum

The type of simulation-based training described in this paper has been delivered to Port Radio Operators at Japanese port radio services for the last eight years, and the outlined approach reflects that established practice. This proposal draws on practitioner experience and documented operational conditions at Japanese VTS centres compiled from JCG guidance and the Tokyo MARTIS User Manual (Japan Coast Guard, 2024; Tokyo Wan Vessel Traffic Service Center, 2023). The contribution this paper outlines is a formalised, transferable curriculum structure and an accompanying rubric-based assessment model for the training. This proposed formalisation has not yet been independently validated. Suggestions for the implementation and validation of this proposal as a customisable programme are outlined later in the paper. Figure 1 summarises the design-to-validation workflow, the later stages of which are detailed in Section 4.

Figure 1. Curriculum Design and Validation Workflow



The platform uses AIS-display-driven simulation in which trainees assume the PRO role at a VHF station linked to a dynamic traffic picture. Unlike vessel-centred bridge simulators, the design is shoreside and communication-centred: trainees interpret an AIS/radar display and manage radio traffic from the port radio room. Programme scenarios use realistic vessel names, call signs, and cargo data taken from various Japanese ports. The scenario instructor controls for variables such as weather, visibility, vessel behaviour, and incident timing simulator files created before each session.

3.1. Scenario Design: Japan-Specific Operational Conditions

The five scenario categories account for communication demands that have been documented in Japanese VTS operations. The selection of scenarios is based on the frequency of appearances from training sessions with Japan's major port radio service groups, not formal incident-frequency data. Validating selections against JCG data is a priority that was outlined in Section 4. Munim et al. (2023) performed a systematic review of maritime simulator training, noting that scenario design remains under-theorised and inconsistently documented. Effective scenarios have been shown to depend on functional congruence between realistic operations and clear learning objectives (Harrington, Sellberg and Lindwall, 2025). These findings were part of the motivation for making the selection rationale explicit in the final column of Table 1.

Table 1. Scenario Overview

Scenario	Japan VTS Anchor	Core Trainee Task	Selection Rationale (primary competency · risk · exposure · training value)*
Grounding	Kanmon/Kurushima Kaikyo — narrow channels, minimal margin for delay	Identify track deviation from AIS before vessel calls; issue SMCP traffic advisory; escalate to JCG	Sensor literacy; high risk (narrow channel, minimal recovery margin); trains pre-emptive AIS detection
Medical Emergency	Tokyo MARTIS — dual-language operations across a single watch	Apply PAN PAN; coordinate with MRCC; sustain the broader traffic picture in a mixed-language environment	Emergency procedures; life-safety, high language complexity; trains emergency response under load
NUC (Not Under Command) Vessel	Tokyo Wan — high-density designated tracks; disabled vessel creates cross-stream risk	Identify NUC from anomalous AIS; broadcast SECURITÉ; coordinate traffic separation; initiate rather than respond to calls	Sensor literacy; high collision risk in dense tracks; trains AIS anomaly detection and proactive coordination
Traffic Lane Violation	Osaka MARTIS — fishing vessel incursions in designated lanes	Issue corrective advisory with correct message markers; log; escalate through graduated re-contact if non-compliant	Local procedures; frequent (Akashi fishing incursions); trains escalation discipline
Non-compliance	Tokyo MARTIS — mandatory pre-entry and position reporting for specific vessel classes	Execute standardised re-contact procedures; escalate on failure; maintain a complete communication log	SMCP + local procedures; routine high-frequency reporting; trains phraseology precision and logging

*Selection rationale reflects practitioner judgment; the exposure/frequency element is the one to be confirmed or refined against JCG incident-frequency data (validation priority 2, Section 4).

As noted in Section 2, each scenario trains for SMCP proficiency and human factors in parallel. Table 1 identifies additional primary competencies for each case, and a sixth scenario targets sensor literacy as the primary assessed competency. This scenario, which could cover content such as the correlation of conflicting AIS and radar tracks, is noted as a design option for piloting.

3.2. Assessment Framework

In this proposed framework, a trained instructor assesses each scenario across three dimensions. Inter-rater reliability (IRR) is treated as a design requirement, so formal IRR testing is the first validation priority (see Section 4). Before live assessments, instructors would achieve reliability by successfully completing calibration sessions using benchmark recordings. At least two instructors are required, and scores are cross-checked before finalisation. Each dimension is scored on a four-level scale defined by observable features to reduce scorer subjectivity. Phraseology Accuracy concerns the structural correctness of the message; Communication Clarity, the intelligibility of its delivery.

Table 2. Assessment Rubric: Four-Level Descriptors

Dimension 1: Phraseology Accuracy — scored against a message-format checklist derived from the IMO SMCP (IMO, 2001), covering call procedures, message markers (e.g., MAYDAY RELAY, PAN PAN, SECURITÉ, TRAFFIC ADVISORY), message structure, and closing procedures. Compliance percentages are indicative and subject to calibration through piloting.

Level	Descriptor
4 – Proficient	All required message markers and SMCP formats used correctly; no procedural omissions. Checklist compliance ≥ 90%.
3 – Competent	Most markers and formats correct; minor omissions or sequencing errors that do not compromise structural completeness. Compliance 75–89%.
2 – Developing	Required markers or formats missing or incorrectly applied; errors affect structural completeness of operational content. Compliance 60–74%.
1 – Insufficient	Frequent omissions or incorrect SMCP application; structural content fails to meet operational requirements. Compliance < 60%.

Dimension 2: Decision Quality — assessment of scenario identification, escalation sequencing, and demand management.

Level	Descriptor
4 – Proficient	Situation correctly identified; escalation to correct authority without undue delay; concurrent demands managed without loss of situational awareness.
3 – Competent	Situation correctly identified; escalation appropriate but delayed or marked by minor procedural hesitation; concurrent demands managed with some difficulty.
2 – Developing	Situation identification delayed or initially incorrect; escalation misdirected or omitted until prompted; concurrent demands cause loss of task tracking.
1 – Insufficient	Situation type misidentified or not identified; escalation absent or misdirected; unable to manage more than one demand stream.

Dimension 3: Communication Clarity — assessment of pace, articulation, pronunciation, and repair under realistic radio conditions, with particular attention to features of L2 English production that affect intelligibility in Japanese maritime contexts (Uchida and Sugimoto, 2023).

Level	Descriptor
4 – Proficient	Appropriate pace with clear articulation of SMCP keywords; repair strategies used effectively; disambiguation without external prompting.
3 – Competent	Generally clear delivery; occasional pacing or pronunciation issues that do not prevent comprehension; repair partially successful.
2 – Developing	Pace unsuitable for reliable reception; pronunciation of SMCP terms impedes comprehension; relies on repetition rather than reformulation.
1 – Insufficient	Delivery largely unintelligible under simulated radio conditions independent of structural correctness; no effective repair strategies; breakdowns unresolved.

A scenario pass requires a minimum score of 3 (Competent) on all three dimensions; a score of 2 triggers targeted remediation, and a score of 1 requires full scenario repetition. The weighting that was assigned to each scenario indicates its dominant performance demand. Emergency scenarios (medical emergency, NUC) weight Decision Quality, non-compliance weights Phraseology Accuracy, and groundings and traffic lane violations were equally weighted in all three dimensions. These thresholds and weights are provisional — further calibration after piloting is expected. Sessions should be recorded, ideally with a time-coded matrix for instructor debriefing. Video recording is optional but allows trainees to review their own performance. Over time, records of phraseology accuracy and response latency are the most actionable measure of development.

3.3. Alignment with IALA V-103/1

Table 3 maps each scenario category with its primary and secondary competency area in accordance with V-103/1 (IALA, 2022). Language and Communication is listed as a secondary competency in the first four scenarios, but in the non-compliance scenario, it is listed as primary. This designation is due to the idea that the management action utilises standardised SMCP re-contact calls and associated log entries. The framework was based on V-103/3 OJT content and supports V-103/5 CPD revalidation.

Table 3. Scenario-to-V-103/1 Competency Mapping

Scenario	Primary V-103/1 Competency	Secondary Competency
Grounding	Traffic Management	Language and Communication
Medical Emergency	Emergency Situations	Language and Communication
NUC Vessel	Emergency Situations	Language and Communication
Traffic Lane Violation	Traffic Management	Language and Communication
Non-compliance	Language and Communication	Traffic Management

The categorisations listed in Table 3 work as specific performance criteria. In the grounding scenario, for example, AIS-based detection of course deviation is used to practise hazard recognition, while timely communication is assessed through the timing, structure, and clarity of the given advisory.

4. Challenges and Future Directions

Maritime English proficiency assessment. Japan's PROs communicate primarily in Japanese for intra-company and domestic vessel communications, so there is a need for ongoing English SMCP training to maintain proficiency for foreign-flag interactions. Simulation performance data (accuracy, correction patterns, and clarity) can provide specific components from which maritime English can be assessed.

Emerging technologies. AI decision-support tools and the continued shift towards Maritime Autonomous Surface Ships (MASS) will reshape PRO communication demands (Miyoshi et al., 2022; Kondo et al., 2025). Training frameworks will need to incorporate learning how to deal with AI-generated advisories. An operational risk is that operators under workload pressure may stop checking protocols and forego the shore-side communication adjustments that autonomous operations require.

Limitations and validation priorities. This paper discusses a design proposal grounded in professional practice and operational analysis. The simulator-based PRO training outlined in this paper has been delivered in Japan for the last eight years and counting. For future development, implementation, and customization, the programme should undergo a systematic, formal evaluation of the curriculum structure and assessment rubric proposed here. Four validation priorities have been identified and suggested for future evaluations: (1) establish inter-rater reliability for the assessment rubric; (2) compare scenario selection against JCG incident-frequency data to further refine the set of categories; (3) run a structured study with Japanese PRO trainees to measure pre- and post-training competency gains; and (4) where data is available, compare simulation performance/experience with operational performance to evaluate transfer of training.

5. Conclusion

Japan's VTS network is well-developed and operates efficiently, but training for Port Radio Operators still has room for further development. The curriculum proposed in this paper addresses that developmental gap through five scenario categories that are grounded in Japanese operational conditions and assessed through a rubric aligned to IALA V-103/1 competency criteria.

The training practices discussed in this paper have been in operational use at Japanese port radio services for eight years and counting. This paper proposes a pathway for the training programme to undergo formalisation and structured validation into a transferable curriculum and assessment framework to allow for wider adoption and regional customisation. For the IAMU community at large, this framework offers a design model for PRO training adaptable to other regional settings through local scenario development, validation, and customisation.

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Appendix A. SMCP Phraseology Accuracy Checklist (Dimension 1)

Each category is scored Met / Partial / Not Met per transmission; the percentage met maps to the Table 2 compliance bands (≥90%, 75–89%, 60–74%, <60%).

Category	Checked elements
Initial call	Called/calling station identified in correct order; working-channel switch acknowledged; "OVER" used to hand over
Message marker	Appropriate marker applied (INSTRUCTION, ADVICE, WARNING, INFORMATION, QUESTION, ANSWER, REQUEST, INTENTION); correct distress/urgency/safety signal where applicable (MAYDAY, PAN PAN, SECURITÉ, MAYDAY RELAY)
Message body	One function per transmission; numbers, call signs, and letters per SMCP spelling conventions; positions, times, and units in standard form
Readback / acknowledgement	Safety-critical content read back; corrections via "MISTAKE … CORRECTION …"; receipt confirmed ("UNDERSTOOD" / "ROGER")
Repair	Breakdowns resolved with "SAY AGAIN", "SPELL", or QUESTION/ANSWER rather than ad hoc repetition
Closing & log	Exchange closed correctly ("OUT"); channel released; complete log entry (time, vessel, action, outcome)

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Development and Validation of a Specialized Questionnaire for Measuring QoS of Ferry Port: A Case Study in Dalian

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Abstract: This study addresses a research gap by developing and validating a specialized questionnaire to evaluate port ferry quality of service. It integrates traditional factors (accessibility, signage, safety, etc.) with emerging elements like digital services. Data was collected via a week-long survey at the Dalian Bay Shipping Center in China. Employing Exploratory Factor Analysis, the tool demonstrated excellent reliability (Cronbach's alpha: 0.982-0.995) and validity. This robust instrument enables future analysis of how specific service factors influence passenger satisfaction, revisit intention, and recommendation behavior.

Keywords: Quality of Service, Ferry Port, Survey, Validation, Passenger maritime transportation

1. Introduction

In recent years, with the development of ocean shipping, it has made a significant contribution to economic growth and employment in various countries. Consistent and reliable scheduled services built customer confidence and help improve overall customer satisfaction (Elmi *et al.*, 2023). The rise of the experience economy has shifted how maritime services are judged. The evaluation and optimization of transportation service quality have become a focal point for both academic research and management practice (Mikuličić *et al.*, 2024).

Passenger perception served as a crucial basis for evaluating the quality of passenger transportation services (de Abreu e Silva and Bazrafshan, 2013). Consequently, user satisfaction was often regarded as a core indicator for measuring service quality (Mandhani, Nayak and Parida, 2020). Conceptually, service quality can be understood as users' comprehensive evaluation of the service experience. The evaluation hinged on diverse attributes, such as transportation environment, accessibility, signage systems, safety and security, public facilities, comfort and convenience (Hernandez and Monzon, 2016). Within the port and shipping service literature, Whether port infrastructure acted as a key determinant of passenger satisfaction with port services has been investigated in (da Luz *et al.*, 2022). Their analysis adopted the perspective of ferry industry stakeholders. However, the existing body of research tends to treat port satisfaction as an isolated antecedent of specific behavioral intentions. How port experiences are integrated into and shaped passengers' perceptions of the overall journey remains insufficiently understood (Lu, Weng and Chen, 2020).

Further analysis reveals that existing studies on the influence of port attributes also have significant limitations. On the one hand, empirical conclusions concerning several key variables remain inconsistent. For instance, the importance, and even statistical significance, of port safety attributes varies substantially across contexts, and the underlying mechanisms driving these effects are still unclear (Baños-Pino and Tovar, 2025). On the other hand, research perspectives have failed to fully incorporate emerging factors such as information and communication technology (Rungroueng, 2024). This omission limits scholarly attention to core elements of the modern port environment, most notably digital services and smart guidance systems. Taken together, these gaps constrain the ability of existing theoretical frameworks to capture the let alone reliably measurement and the full scope of service quality in contemporary ports, especially in ferry port settings.

Therefore, to address these research gaps and advance both theoretical development and the practical needs of precise management, this study develops and validates an evidence-based measurement questionnaire with demonstrated reliability and validity. To this end, the instrument is designed to systematically identify and evaluate the key factors that drive ferry service quality at port level. Despite the existence of general service

quality measurement models (Sumaedi1, Bakti and Yarmen, 2012), the port environment has unique characteristics and complexities, regarding passenger and vehicle circulation flows, facility functions, and perceived safety. This creates an urgent need for a specialized assessment tool tailored to the port's specific operational context. This study will cover the entire passenger touchpoint chain: from arrival and wayfinding signage through waiting areas and terminal facilities, to overall perceived safety. It is intended to serve as a reliable diagnostic and improvement benchmark for both academic research and industry management.

2. Related studies

Quality of Service (QoS) refers to an organization's ability to meet and exceed user expectations. Concretely, it is assessed by comparing the gap between user expectations and actual perceived performance (Prakash, 2018). In the passenger transportation sector, service quality denotes the overall experience perceived by passengers. It encompasses multiple dimensions, such as reliability, safety, flexibility, convenience, and care. It also hinges on more tangible operational factors, such as speed, comfort, system efficiency, and environmental sustainability (de Oña, de Oña and López, 2016).

Relevant research aims to identify key factors influencing service quality through various statistical methods. Research on service quality measurement in the transportation sector has advanced considerably; nevertheless, measurement approaches are commonly organized into two broad families: qualitative and quantitative. Qualitative methods include interviews, questionnaires, and field surveys. They elicit users' descriptive evaluations of service attributes, usually against predefined scales. Quantitative approaches, by contrast, draw on regression analysis, structural equation modeling (SEM), and multi-criteria decision analysis (MCDA). Their objective is to formalize the relationship between specific service attributes (independent variables) and overall satisfaction (dependent variable) (Mikuličić *et al.*, 2024). These methods help orient service-improvement priorities. At the same time, they must be adapted to contextual factors to remain valid and actionable, such as users' lifestyles, socio-demographic characteristics, trip purposes, and travel-mode choices (Guirao, García-Pastor and López-Lambas, 2016).

Existing research indicates that safety and the environment are typically regarded as the most critical factors in service quality assessments (Hernandez and Monzon, 2016; Kim *et al.*, 2018). Information accessibility, comfort, and convenience are also considered important factors influencing service quality, particularly the quality of the environment surrounding stations (Lois, Monzón and Hernández, 2018). Within the port and shipping service research, scholars have approached service quality from several complementary angles. Firstly, terminal service quality, efficient customs clearance procedures, continuous upgrades to port hardware and software facilities, and factors based on port attributes (such as hygiene, safety, comfort, and transportation convenience) have been shown to shape passengers' overall travel perceptions, satisfaction, and willingness to recommend (Whyte, 2017; Sun *et al.*, 2019; Rungroueng, 2024). Secondly, port security, infrastructure, and supporting services also exert a positive influence on passenger loyalty and overall satisfaction. These findings point to a clear managerial imperative for decision-makers to sustain and strategically increase investment in the port service environment (Brida *et al.*, 2012). Furthermore, attributes related to the destination's basic functions and core experiences (such as port facility efficiency, transportation convenience, and public safety) are considered the most important factors driving overall satisfaction (Ozturk and Gogtas, 2016).

3. Case study and survey

3.1. Case study

The data for this study were collected using a questionnaire survey at the Liaoyu Dalian Bay Shipping Center. The Liaoyu Dalian Bay Shipping Center, a ro-pax port that officially opened on December 28, 2025, is located within the Liaoyu Group industrial park in Dalian Bay Subdistrict, Ganjingzi District, Dalian City, Liaoning Province, with a total investment of 300 million yuan. The project features two 50,000-ton-class and two 30,000-ton-class passenger-ro-ro berths, as well as one 10,000-ton-class passenger-cargo ro-ro berth, providing berthing capacity for 10 large passenger-ro-ro vessels. It is complemented by a 75,000-square-meter security screening and logistics area and a 2,750-square-meter shipping service center modeled after international airports. Among the nine passenger-cargo Ro-Ro vessels currently operating the Dalian‑Yantai

route, two are capable of transporting new energy vehicles. The facility handles 1.7 million passenger trips and 700,000 vehicle trips annually, with operational efficiency enhanced by panoramic surveillance, smart boarding, digital ticketing, and automated security screening systems. During the Spring Festival travel rush, the center serves as one of Dalian's five designated port passenger terminals (China Water Transportation, 2025).

3.2. Questionnaire

The survey questionnaire is divided into three main sections. The first section covers basic travel characteristics and travel behavior, comprising eight specific items that address the purpose of travel, modes of transportation used to reach the terminal from both within and outside the city, ticket purchasing methods, frequency of using online services (such as ticket booking and information inquiries), and the overall ferry travel experience. The second section evaluates port infrastructure. This section comprises 7 sub-scales with a total of 22 specific measurement items. Respondents are asked to rate each item on a 5-point Likert scale, where items B1 through B4, as well as B6 and B7, range from 1 (Strongly Disagree) to 5 (Strongly Agree); item B5 (Overall Satisfaction) ranges from 1 (Very Dissatisfied) to 5 (Very Satisfied). The dimensions measured in this module include: transportation convenience, clarity of signage, infrastructure and environment, perceived safety, overall satisfaction, willingness to revisit, and willingness to recommend. The third section covers demographic variables, comprising 7 items (C1 to C7), including gender, age, type of ferry ticket purchased, educational level, marital status, occupation, and monthly income. Participants completed the questionnaire online by scanning a QR code with their mobile phones.

In terms of demographics, the sample covered travelers of different genders, ages, income levels, and educational backgrounds, accurately reflecting the demographic profile of the route's primary passenger base. Second, regarding travel behavior, the primary purposes of travel were "business trips" and "tourism/visiting relatives"; when traveling from city centers to the port, the highest proportion of passengers chose "taxis/ride-hailing services"; "online ticketing" was by far the most common method of purchasing tickets, and passengers generally used online channels to check vessel schedules and other information, demonstrating a high degree of reliance on digital services.

3.3. Data

The data for this study were collected using a questionnaire survey method during the New Year's holiday period from December 29, 2025, to January 4, 2026, at the Liaoyu Dalian Bay Shipping Center. In this study, the data underwent preprocessing. First, missing values in the sample were handled: for numerical variables, missing values were imputed using the median of the corresponding variable. After processing, a total of 489 valid samples were retained, ensuring the statistical power of the subsequent regression analysis. Second, for each theoretical dimension, the scores of the corresponding measurement items were averaged to calculate a composite score for that dimension, thereby preserving the core information of the latent variable.

4. Results

4.1. Descriptive statistics and confirmatory analysis

Methods such as regression, confirmatory, and exploratory factor analysis are generally the most suitable for evaluating service quality because they help reduce the dimensionality of the dataset (Mikuličić *et al.*, 2024).

Table 1 shows the descriptive statistics and correlations among the variables in the study. In terms of perceived port service evaluation, passengers gave the highest ratings to the basic information system and safety services. Specifically, flight information, waiting hall signage, and parking signage scored high, and the perceptions of overall safety and personal security were also very high, indicating that the port performs excellently in these core services. In contrast, evaluations of facilities related to comfort and convenience were relatively lower, such as convenience facilities, waiting areas, and willingness to share experiences on social media, indicating that there is room for improvement in these aspects. Overall satisfaction and willingness to recommend were at a good level but still have potential for enhancement.

Regarding travel characteristics, the mean values for passengers' travel purposes indicate that leisure tourism is predominant, and the mean values for previous sailing experiences show that most passengers have some sailing experience. The sample is balanced by gender. Most respondents are aged 25–45, are housed in

third-class cabins, and report a monthly income in the CNY 4,001–8,000 range. That is consistent with the mass-tourism market segment targeted by the cruise line.

Table 1. Descriptive statistics.

Variable	N	Range	Min	Max	Mean	Standard Deviation	Variance
Travel Purpose	489	4	1	5	2.26	1.128	1.272
Previous Ship Travel Experience	489	3	1	4	2.87	1.026	1.053
Parking Signage	489	4	1	5	4.04	0.741	0.549
Flight Info	489	4	1	5	4.06	0.728	0.53
Waiting Hall Signage	489	4	1	5	4.05	0.738	0.545
Luggage Customs	489	4	1	5	3.91	0.78	0.609
Amenities	489	4	1	5	3.81	0.824	0.679
Restrooms	489	4	1	5	3.9	0.791	0.626
Waiting Area	489	4	1	5	3.86	0.81	0.656
Quietness	489	4	1	5	3.85	0.817	0.667
Lighting	489	4	1	5	4	0.707	0.5
Personal Safety	489	4	1	5	4.02	0.699	0.489
Overall Safety	489	4	1	5	4.03	0.696	0.485
Overall Satisfaction	489	4	1	5	3.87	0.773	0.598
Willingness To Revisit	489	4	1	5	3.89	0.765	0.585
Preference For Port	489	4	1	5	3.87	0.779	0.607
Word Of Mouth	489	4	1	5	3.89	0.773	0.597
Social Media Share	489	4	1	5	3.8	0.852	0.726
Encourage Others	489	4	1	5	3.89	0.774	0.598
Gender	489	1	1	2	1.48	0.5	0.25
Age	489	7	1	8	4.52	1.173	1.377
Cabin Class	489	6	1	7	4.3	1.803	3.252
Monthly Income	489	6	1	7	4.1	1.567	2.454

This study examined the reliability and validity of latent variables related to port services using confirmatory factor analysis (CFA). As shown in Table 2, the measurement models for each dimension exhibited excellent statistical properties. First, the Cronbach's alpha coefficients for all latent variables ranged from 0.982 to 0.995, far exceeding the acceptable threshold of 0.70. This indicates that the measurement scales possess extremely high internal consistency reliability and can consistently reflect their corresponding constructs. Second, the KMO values ranged from 0.60 to 0.886, all meeting the requirement of being greater than 0.60. Furthermore, the significance level of Bartlett's sphericity test for all dimensions was $P < 0.001$, indicating significant intercorrelations among the variables and confirming their suitability for factor analysis. Regarding convergent validity, each latent variable yielded a single principal component, with cumulative variance explained exceeding 96% for all dimensions. This indicates that the scales effectively capture the core information of their theoretical constructs, demonstrating high convergent validity. In summary, the measurement model constructed in this study meets high standards in terms of both reliability and validity,

providing a solid empirical foundation for subsequent multiple regression analysis and testing of theoretical hypotheses. It also corroborates the scientific validity and reliability of the various service dimensions (such as facility environment, willingness to revisit, and willingness to recommend) at the measurement level.

Table 2. Statistics of reliability and validity

Latent Variable	Number of Items	Cronbach's Alpha	KMO	Significance	Convergent Validity
B_1	5	0.992	0.747	P<0.001	One component extracted, explaining 96.95% of variance
B_2	3	0.991	0.795	P<0.001	One component extracted, explaining 98.245% of variance
B_3	5	0.99	0.884	P<0.001	One component extracted, explaining 96.037% of variance
B_4	4	0.995	0.886	P<0.001	One component extracted, explaining 98.665% of variance
B_6	2	0.988	0.6	P<0.001	One component extracted, explaining 98.831% of variance
B_7	3	0.982	0.733	P<0.001	One component extracted, explaining 96.836% of variance

4.2. Regression analysis

A multiple regression analysis was used to examine the impact of various service factors on overall port satisfaction as following:

$$\boldsymbol{Y_i = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \beta_3 X_{3,i} + \beta_4 X_{4,i} + \beta_5 X_{5,i} + \beta_6 X_{6,i} + \varepsilon_i}\ .$$

This study employs this multiple linear regression model to analyze the impact of each service dimension on overall satisfaction. The specific model is defined as:

$$B_{5,i} = \beta_0 + \beta_1 B_{1,i} + \beta_2 B_{2,i} + \beta_3 B_{3,i} + \beta_4 B_{4,i} + \beta_5 B_{6,i} + \beta_6 B_{7,i} + \varepsilon_i\ ,$$

where the subscript i denotes the sample index. This study includes a total of n = 489 valid samples, so i = 1, 2, ⋯, 489. For simplicity, the model is written in matrix form: $Y = \beta X + \varepsilon$. Here, Y is an $1 \times n$ column vector containing the $B_{5,i}$ for all samples. X is an $7 \times n$ design matrix, where each row corresponds to a sample, and the columns represent the constant term and the standardized scores of the six independent variables ($B_{1,i}$ to $B_{7,i}$). β is a 1×7 coefficient vector (β_0 to β_6). ε is an $n \times 1$ random error vector. Parameter estimation by ordinary least squares yields the following regression equation:

$$B_5 = -2.78 \times 10^{-17} + 0.0194B_1 - 0.0191B_2 + 0.2818B_3 + 0.0146B_4 + 0.4350B_6 + 0.2307B_7 + \varepsilon\ .$$

Table 3. Multiple regression analysis results

Latent Variable	Coefficient	Standard Error	*t*-value	*p*-value	Significance	Significance Direction of Effect	Notes
B_1	0.0194	0.0181	1.0726	0.284	Not significant	Positive	Convenient transportation
B_2	-0.0191	0.0228	-0.8407	0.401	Not significant	Negative	Easy to identify signage
B_3	0.2818	0.045	6.2671	<0.0001	Significant	Positive	Facility environment
B_4	0.0146	0.0234	0.6271	0.5309	Not significant	Positive	Sense of safety

B_6	0.435	0.0793	5.4884	<0.0001	Significant	Positive	Willingness to revisit
B_7	0.2307	0.0774	2.979	0.003	Significant	Positive	Willingness to recommend

A multiple regression analysis was conducted to examine the impact of various service factors on overall port satisfaction, and the results are shown in Table 3. The regression coefficient for the facility environment is 0.2818, indicating a very strong positive predictive effect. The coefficient for revisit intention is the highest, making it the most critical factor affecting satisfaction. Recommendation intention also has a significant positive impact. In contrast, convenience of transportation, ease of recognizing signage, and sense of safety have no significant direct effect on satisfaction. This finding indicates that the facility environment and intention-related variables are central in explaining passenger satisfaction. Enhancing passengers' long-term behavioral intentions (revisit and recommendation) and optimizing physical facilities may be the most effective ways to improve overall port service satisfaction.

5. Conclusions and Perspectives

This study aims to develop and validate a specialized questionnaire for assessing port service quality, in order to address the current research gap in comprehensively considering both traditional and emerging service elements. Through an empirical survey of passengers at the Dalian Bay New Port Passenger Center, the study constructed an evaluation tool with good reliability and validity, and analyzed the specific mechanisms by which port service attributes affect overall passenger satisfaction.

The results indicate the following findings. Firstly, the developed questionnaire demonstrates excellent measurement performance across six dimensions: transportation accessibility, clarity of signage, facilities and environment, sense of safety, intention to revisit, and willingness to recommend. It can serve as a reliable tool for evaluating port service quality. Secondly, passengers rated core informational services and safety services the highest, while ratings for comfort facilities and willingness to share were relatively low, suggesting that the latter should be the focus of future service improvements. Finally, multiple regression analysis shows that facilities and environment are direct predictors of satisfaction, while intention to revisit and recommend exhibits the strongest driving effect, highlighting the mutually reinforcing relationship between passenger loyalty behaviors and satisfaction perception. In contrast, transportation convenience, signage clarity, and sense of safety, while necessary foundational factors, did not show statistically significant direct effects, possibly indicating a 'hygiene factor' characteristic.

In summary, this study not only developed a port service quality evaluation tool, but also empirically identified the core drivers of satisfaction, providing a decision-making basis for port management. Based on the conclusions and limitations of this study, future research could further explore the following aspects: at the theoretical level, investigating the indirect impact of basic attributes on satisfaction through mediating variables such as perceived value, and recommending the inclusion of 'digital service quality' in the scale, while using methods like structural equation modelling to clarify complex path relationships among multiple variables. At the management practice level, it is recommended that port managers use specialized tools for regular service monitoring, focus on optimizing facilities and environment, and build a loyalty-oriented service system to transform satisfied passengers into loyal advocates. At the research scope level, future studies could conduct cross-case comparisons across different regions and port types to verify the generalizability of the findings, or utilize longitudinal tracking and qualitative research to explore the long-term effects of service improvements and the underlying mechanisms of passenger experiences.

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AtoN within the Regulatory Framework of Navigation: Evolution from Physical to Digital Navigational Solutions

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Abstract: Aids to Navigation (AtoN) represent one of the fundamental elements of the navigational safety system and have traditionally occupied an important position within maritime law. Although they were long understood primarily as physical means, such as lighthouses and buoys, technological development has expanded their scope to include digital and virtual navigational solutions. This evolution raises a number of legal and regulatory issues, particularly regarding the normative definition of navigational aids, the delineation of responsibilities among relevant stakeholders, and the capacity of the existing legal framework to adapt to technological change. The paper analyzes the regulatory evolution of AtoN through the framework of the International Convention for the Safety of Life at Sea (SOLAS), the United Nations Convention on the Law of the Sea (UNCLOS), and the International Maritime Organization (IMO) e-Navigation initiative, highlighting the transition from traditional physical navigational aids toward digital and virtual navigational solutions. The paper argues that the interaction between technologically neutral treaty law and adaptive soft law standards enables the international regulatory framework to accommodate digital transformation while preserving the fundamental principles of navigational safety.

Keywords: Aids to Navigation (AtoN); SOLAS, UNCLOS, e-Navigation, IALA standards

1. Introduction

Aids to Navigation (AtoN) have historically played a central role in ensuring navigational safety and the effective organization of maritime traffic. Their primary function is to ensure safe and efficient navigation, reduce the risk of maritime accidents, and contribute to the overall safety and organization of maritime traffic. In this context, AtoN are not viewed merely as technical navigation tools, but also as part of a broader legal and institutional framework aimed at ensuring the safety of vessel movements at sea (IALA, 2023).

Historically, navigational aids developed primarily as physical and static elements of navigational infrastructure. These included lighthouses, buoys, light and sound signals, as well as other visual and auditory markers intended to indicate navigable routes, warn of hazards, and define safe navigation zones. In this early stage of development, AtoN had a relatively stable function and a clearly recognizable form, both technically and legally, since they were directly associated with the physical marking of maritime waterways.

However, the contemporary development of maritime technology, particularly processes of digitalization, automation, and integration of navigational systems, has led to a significant transformation of the traditional concept of navigational aids. Physical navigation aids are increasingly being supplemented by digital and virtual solutions, including Automatic Identification System (AIS)-based AtoN services and virtual navigational aids displayed through integrated electronic navigation systems such as the Electronic Chart Display and Information System (ECDIS) (IMO, 2009; IALA, 2021a). This shift does not merely represent a technical improvement, but rather reflects a broader evolution of the AtoN concept, affecting their definition, normative interpretation, and practical application within the maritime safety system.

Despite these technological developments, the key international legal instruments, particularly the United Nations Convention on the Law of the Sea (UNCLOS) and the International Convention for the Safety of Life at Sea (SOLAS), continue to adopt a functional approach to navigational aids. These conventions establish the fundamental obligations of States regarding navigational safety and the provision of navigational services while maintaining a high degree of technological neutrality (UNCLOS, 1982; SOLAS, 1974). Rather than prescribing

specific technical solutions or defining the form of AtoN systems, they focus on functional requirements such as ensuring safe navigation, marking navigational hazards, and regulating navigable routes.

Such an approach enables States to independently choose the technologies and methods through which these objectives will be achieved, thereby ensuring the flexibility and long-term applicability of the international legal framework under conditions of rapid technological development in maritime navigation (Garcia-Carriazo et al., 2023). At the same time, technical standards and guidelines developed by the International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) are gaining increasing practical importance, despite their legal status remaining within the domain of so-called soft law instruments, with indirectly binding effects through State practice and the implementation of international conventions (Boyle, 2010).

Accordingly, the contemporary concept of AtoN can no longer be viewed exclusively through its traditional physical dimension, but rather through the dynamic relationship between technological development, functional navigational safety requirements, and the evolution of the international regulatory framework.

This paper adopts a doctrinal and analytical approach, examining international legal instruments, technical standards developed by the International Maritime Organization (IMO) and IALA, as well as recent academic literature addressing digital navigation and maritime cybersecurity. The paper addresses the question of how the technologically neutral framework of international maritime law accommodates the digital transformation of AtoN. By analyzing the interaction between treaty law and soft law standards, the paper highlights the evolving regulatory balance between legal stability and technological adaptability in the context of digital AtoN systems.

2. Traditional Concept of Aids to Navigation in Law and Practice

Traditionally, AtoN have represented one of the fundamental elements of the navigational safety system, acquiring a clearly defined functional and legal role through the historical development of maritime transport (Hasbullah, Osnin and Mohd Salleh, 2023). Their importance derives not only from their technical function in navigation, but also from the fact that they constitute an integral part of the organized system of navigational safety management. In the broadest sense, AtoN encompass all means and objects intended to guide, mark, and ensure the safe movement of vessels, enabling participants in maritime navigation to maintain reliable orientation and timely identify navigational hazards (IALA, 2023).

Within the traditional concept, AtoN are primarily associated with physical navigational aids, including lighthouses, light and sound signals, buoys, coastal marks, and other fixed or floating objects established for the purpose of marking waterways, hazards, or the boundaries of navigational zones. These means represent the oldest form of navigational infrastructure, whose function is based on direct visual and auditory communication with vessels in navigation. Owing to this directness and relative technological simplicity, their role in practice was clearly recognizable, which contributed to their early acceptance as a standard element of navigational safety.

Within the traditional navigational framework, a clear functional distinction existed between AtoN as external maritime infrastructure maintained by coastal States and onboard navigational equipment operating as part of the vessel's internal technical system. While coastal States were responsible for the establishment and maintenance of navigational aids, the operation and adequacy of onboard navigational equipment remained within the sphere of responsibility of the flag State and shipowner. Although this distinction initially developed primarily through navigational practice rather than formal legal regulation, it gradually acquired greater normative significance with the development of the modern international legal framework governing navigational safety (UNCLOS, 1982; Rothwell and Stephens, 2016).

The legal dimension of navigational aids becomes particularly evident through their role within the navigational safety system. From a legal perspective, traditional AtoN perform multiple functions. Most importantly, they represent an instrument through which States fulfill their obligation to ensure navigational safety within internal waters and territorial seas. This obligation derives from international law of the sea and national legislation, under which States assume responsibility for the establishment, maintenance, and supervision of navigational aids (Churchill, Lowe and Sander, 2022).

In addition, AtoN play an important role in the prevention of maritime accidents, particularly collisions and groundings, by enabling vessels to identify hazards in a timely manner and safely navigate through

waterways. Their function is therefore not limited to the physical marking of maritime space, but also includes the creation of conditions necessary for the effective implementation of navigational rules and maritime safety standards (COLREGs, 1972; Cockcroft and Lameijer, 2011).

Accordingly, AtoN represent the operational foundation enabling the practical application of navigational safety rules. Their role is directly connected with the Convention on the International Regulations for Preventing Collisions at Sea (COLREGs), which governs the conduct of vessels in different navigational situations. Although COLREGs prescribe how vessels must navigate and react in order to avoid collisions, their effective implementation presupposes that the crew possesses a clear spatial understanding of the navigational environment. Navigational aids provide precisely such information by marking waterways, hazards, and navigational zones, thereby ensuring the conditions necessary for the consistent application of COLREGs in practice.

3. International AtoN Regulatory Framework

3.1. Normative Fragmentation of the AtoN Concept

The legal regime governing AtoN in international maritime law is characterized by the absence of a unified and explicit definition within binding international legal instruments. Rather than being regulated as a separately defined legal category, AtoN appear implicitly through functionally formulated State obligations relating to navigational safety, hazard marking, and the organization of maritime traffic.

Neither UNCLOS nor SOLAS provides a comprehensive normative definition of AtoN or prescribes specific technical solutions regarding their implementation. Instead, both conventions adopt a technologically neutral and functionally oriented regulatory approach. Such an approach does not represent a legal gap, but rather a deliberate regulatory model intended to preserve the long-term applicability of international maritime law under conditions of continuous technological development in navigation (Garcia-Carriazo et al., 2023).

In this regard, UNCLOS may be understood as applying an obligation-oriented approach, whereby emphasis is placed on the objectives States are required to achieve, including navigational safety, hazard marking, and traffic organization, while the selection of specific technical and operational measures remains within the discretion of individual States. Similarly, SOLAS establishes functional obligations concerning navigational safety and navigational services without limiting their implementation to particular technological forms of AtoN.

In contrast to treaty-based sources, the detailed technical and operational elaboration of AtoN has largely developed through technical and operational standards. A particularly important role in this respect is played by IALA, whose recommendations, guidelines, and technical standards have become internationally accepted references for the design, implementation, and operation of AtoN systems. Within the broader technological context, the IMO, especially through the e-Navigation concept, has further contributed to the functional expansion of AtoN through the integration of traditional and digital navigational services.

This multilayered normative structure demonstrates that the contemporary regulation of AtoN is based not upon a single comprehensive legal definition, but upon the interaction of treaty law, technical standards, and soft law instruments. Within this framework, IALA represents the most relevant source of the operational understanding of AtoN. AtoN is defined as “a device, system or service, external to a vessel, designed and operated to enhance safe and efficient navigation and maritime traffic” (IALA, 2023). This definition encompasses both traditional physical aids, such as lighthouses, buoys, and markers, as well as modern digital and virtual systems, including AIS-based AtoN.

Within the IMO framework, particularly through the e-Navigation strategy, AtoN are not redefined as a separate legal category; rather, their functional scope is progressively expanded, making them part of an integrated navigational information environment (IALA, 2024) that includes electronic navigational charts, shipboard systems, and shore-based information services (IMO, 2009).

Accordingly, a clear functional division emerges within the contemporary regulatory framework. International conventions such as UNCLOS and SOLAS establish the fundamental legal obligations and general regulatory structure governing navigational safety, while IALA and IMO develop the technical and operational standards necessary for the practical implementation of those obligations. Such interaction between hard law

and soft law enables a flexible and adaptive regulatory system capable of preserving legal stability while simultaneously accommodating continuous technological development in maritime navigation (Boyle, 2010).

3.2. AtoN within the "Hard Law" Framework of International Maritime Law

The provision of AtoN represents one of the fundamental obligations of coastal States within the international legal framework governing navigational safety. Within contemporary international maritime law, this obligation primarily derives from UNCLOS and SOLAS, which together establish the core legal structure governing navigational safety, maritime traffic organization, and navigational services.

Within UNCLOS, the normative framework relating to AtoN is established through several interconnected provisions that collectively define the competences and responsibilities of coastal States regarding navigational safety. Pursuant to Article 21 of UNCLOS, coastal States possess both the right and the obligation to regulate navigational safety and protect navigational aids within the territorial sea, including the establishment and maintenance of AtoN systems. Article 22 further authorizes coastal States to organize navigation through the designation of sea lanes and traffic separation schemes, while Article 24 establishes the obligation to provide appropriate notification of navigational hazards (UNCLOS, 1982).

These provisions demonstrate that AtoN constitute an essential operational instrument through which coastal States implement their broader obligations concerning navigational safety and the organization of maritime traffic. Although UNCLOS does not define AtoN as a separate legal category, it establishes the legal foundation upon which navigational aid systems operate within the maritime domain of coastal States (Rothwell and Stephens, 2016).

At the same time, UNCLOS also establishes an important framework concerning the responsibilities of flag States in matters of navigational safety. Despite the functional distinction between AtoN as external maritime infrastructure and onboard navigational equipment forming part of the vessel's internal technical system, Article 94 of UNCLOS regulates the obligations of flag States relating to the safety of vessels flying their flag. In particular, Article 94(4)(a) requires that vessels carry appropriate nautical charts, nautical publications, and navigational equipment necessary for safe navigation (UNCLOS, 1982, Article 94). In this manner, international maritime law establishes a functional relationship between AtoN maintained by coastal States and onboard navigational systems operating under the responsibility of flag States and shipowners.

SOLAS represents the principal international instrument governing operational navigational safety at sea. Although it does not contain an explicit legal definition of AtoN, its provisions possess significant indirect normative effect through the establishment of concrete obligations concerning navigational safety, navigational services, and navigational equipment onboard vessels.

Particular significance is attached to Chapter V – Safety of Navigation, which, unlike many other SOLAS provisions, applies to almost all vessels on all voyages, subject only to limited exceptions such as warships, non-commercial government vessels, and ships operating exclusively within certain inland waters (SOLAS, 1974, Chapter V). This broad scope of application ensures that the fundamental principles of navigational safety extend beyond the traditional SOLAS regime applicable solely to international commercial voyages.

Within Chapter V, particular importance is attached to provisions governing navigational aids and onboard navigational systems. Regulation 13 addresses the establishment and maintenance of AtoN systems, while Regulation 19 prescribes requirements concerning shipborne navigational systems and equipment. Accordingly, although SOLAS does not regulate AtoN as an autonomous legal institution, it functionally connects navigational aid infrastructure with onboard navigational systems, thereby contributing to a unified framework of navigational safety.

In addition, SOLAS establishes obligations concerning the timely dissemination of information relating to navigational hazards. States are required to take appropriate measures to notify all relevant parties upon becoming aware of dangers affecting navigation. Such obligations play a particularly important role in the prevention of maritime accidents, as timely and accurate navigational information often constitutes a decisive factor in avoiding collisions, groundings, and other navigational incidents (Churchill, Lowe and Sander, 2022).

3.3. AtoN within the Framework of Soft Law and Technical Standards

Unlike international conventions, which establish general State obligations regarding navigational safety, the detailed technical regulation of AtoN has largely developed through soft law instruments, primarily within the framework of IALA and IMO. Although these instruments do not create formally binding legal obligations in the same manner as international conventions, they have acquired considerable normative and operational authority in practice by shaping the technical, organizational, and functional standards governing contemporary navigational systems.

Within the contemporary regulatory framework, IALA occupies a central role in the technical standardization of navigational aids. Through recommendations, guidelines, manuals, and technical specifications, IALA develops internationally accepted principles concerning the design, classification, implementation, and operation of AtoN systems. Particular significance is attached to standards relating to digital and virtual navigational aids (IALA, 2021a), including AIS-based AtoN solutions (IALA, 2008) and virtual AtoN services intended primarily for application in coastal and nearshore waters. These documents establish operational guidance concerning the reliability, interoperability, limitations, and integration of digital AtoN within broader navigational information systems (IALA, 2021c).

At the same time, IMO contributes to the modernization of navigational systems primarily through the development of the e-Navigation concept. Within this framework, navigational safety is increasingly understood as a process based upon the harmonized exchange of digital information between ships and shore-based services. The objective of this approach is to improve situational awareness, navigational decision-making, and overall navigational safety through the integration of data originating from multiple navigational sources. Consequently, AtoN are progressively evolving from isolated physical marking devices into components of an integrated navigational information environment.

Although IALA recommendations and IMO technical guidance formally belong to the category of soft law instruments, their practical influence extends far beyond purely advisory functions. Due to their broad international acceptance and systematic implementation within maritime administrations, hydrographic services, port authorities, and national maritime regulations, these standards frequently operate as quasi-regulatory instruments in practice. Compliance with IALA and IMO technical guidance is often regarded as an essential prerequisite for achieving internationally acceptable levels of navigational safety and interoperability between coastal and shipboard systems.

In this respect, soft law instruments effectively complement the technologically neutral framework established by UNCLOS and SOLAS. While international conventions define the fundamental legal obligations of States concerning navigational safety, technical standards developed within IALA and IMO provide the operational and technological mechanisms necessary for the practical implementation of those obligations. Such interaction between treaty law and technical soft law enables both legal stability and technological adaptability within the international maritime regulatory framework.

Furthermore, the increasing reliance on digital navigational systems demonstrates that contemporary maritime regulation is no longer based exclusively on traditional legal norms, but also on internationally harmonized technical governance. In this context, technical standards increasingly influence the practical interpretation and implementation of navigational safety obligations, even without possessing formally binding legal force.

Accordingly, the modern regulatory framework governing AtoN may be understood as a multilayered system composed of binding international obligations on the one hand, and technical and operational standards on the other. Such a structure enables the continuous modernization of navigational safety systems while preserving the stability and long-term applicability of international maritime law.

4. Digital Evolution of AtoN and Emerging Legal Challenges

Unlike traditional forms of AtoN, which were based on physical objects and the direct visual or auditory perception of seafarers, the contemporary development of AtoN is characterized by their gradual transformation into systems operating through the collection, processing, and exchange of navigational data. This transition does not merely involve the introduction of new technologies, but also a transformation in the nature of

navigational aids themselves – from physical objects positioned at sea to continuously updated informational and communication-based services (IMO, 2009).

Within this process, AIS plays a particularly important role, as it enables the transmission of navigational information without the need for a physical object at sea. In this manner, the concept of virtual navigational aids has emerged, referring to AtoN that exist exclusively in digital form (IALA, 2021a) and are displayed through onboard navigational systems (Mraković and Bošnjak, 2023). Such solutions enable faster and more flexible marking of navigational hazards, particularly in situations where the deployment of physical aids is impractical, temporary, or economically unjustified (IALA, 2021b).

Further technological development, particularly through ECDIS and integrated bridge systems, has resulted in AtoN becoming part of a unified navigational display environment onboard vessels. Within such systems, information originating from multiple navigational sources is integrated and presented as a single operational picture. Consequently, AtoN are no longer merely passive marking devices, but increasingly form part of the navigational decision-making process itself (IMO, 2017).

This transformation is particularly evident within the International Maritime Organization e-Navigation concept, where AtoN are viewed as components of an integrated information exchange system between ship and shore. Within this framework, shore-based and onboard systems become functionally interconnected, while the traditional legal distinction between the responsibilities of coastal States and flag States largely remains preserved.

From a legal perspective, however, the digitalization of AtoN introduces a number of challenges that did not arise in relation to traditional physical navigational aids. Questions emerge regarding the reliability and legal significance of virtual navigational aids, particularly because digital AtoN depend upon communication networks, software systems, electronic displays, and the integrity of transmitted navigational data. Unlike physical AtoN, which can be directly observed and independently verified by navigators, digital systems rely upon the continuous functionality and accuracy of interconnected technological infrastructure (Mraković and Bošnjak, 2023).

In this context, the issue of liability becomes particularly significant in situations involving system malfunctions, signal interruptions, inaccurate data transmission, or erroneous display of navigational information. Within the traditional navigational framework, responsibility was relatively clear and primarily connected to the coastal State responsible for establishing and maintaining navigational aids. In contrast, digital navigational systems involve multiple actors, including coastal authorities, communication service providers, software systems, hydrographic services, and onboard navigational equipment. Consequently, responsibility may become fragmented and distributed among several participants within the navigational information chain (Nawrot et al., 2024).

Additional legal challenges arise from the increasing dependence of digital AtoN systems upon technical standards developed by IALA. Although these standards are widely implemented in practice and possess considerable operational authority, they formally belong to the category of soft law instruments and therefore do not possess directly binding legal force. Nevertheless, they are frequently applied in practice as if compliance were mandatory, particularly in relation to internationally accepted standards of navigational safety and technical interoperability.

At the same time, the growing reliance on digital navigational systems also raises broader concerns regarding cybersecurity, data integrity, and the protection of navigational information against manipulation, interruption, or unauthorized interference (Kanwal et al., 2024). As navigational safety becomes increasingly dependent upon digital information exchange, the reliability and security of communication systems acquire growing legal and operational significance (Park et al., 2023; Progoulakis et al., 2022).

Within these developments, the principle of technological neutrality in international maritime law continues to play an important role. This principle enables new technological solutions to be incorporated into the existing legal framework without requiring constant amendments to international conventions. At the same time, however, the increasing pace of technological development raises questions regarding whether technologically neutral regulation can continue to provide sufficient legal certainty and uniformity in the governance of emerging navigational technologies (Garcia-Carriazo et al., 2023).

It may therefore be concluded that the digitalization of AtoN does not alter the fundamental objective of navigational safety systems, but significantly transforms the manner in which such systems are technically and legally implemented. Consequently, there is a growing need for further harmonization between legal regulation and technical governance in order to ensure reliability, legal certainty, interoperability, and the consistent application of navigational safety standards within contemporary maritime navigation.

5. Conclusion

The evolution of AtoN from traditional physical aids to digital and virtual solutions represents one of the clearest examples of the contemporary transformation of maritime navigation under the influence of technological development. Although the technical methods of their operation and implementation are changing, the fundamental purpose of AtoN remains unchanged – ensuring the safety and efficiency of navigation.

The analysis presented in this paper demonstrates that the absence of a unified legal definition of AtoN within binding international instruments such as UNCLOS and SOLAS does not constitute a normative deficiency, but rather reflects a deliberate preference for a functional and technologically neutral regulatory approach. Such a structure enables the international legal framework governing navigational safety to remain stable and adaptable under conditions of continuous technological development.

At the same time, the growing importance of technical and operational standards developed by IALA and IMO demonstrates the increasing role of technical governance standards within the contemporary governance of navigational safety. Although these standards do not possess formally binding legal force, their widespread implementation within maritime administrations and navigational practice gives them substantial operational and quasi-regulatory significance.

The digitalization of AtoN, particularly through AIS-based and virtual navigational aids, introduces new legal and operational challenges relating to reliability, interoperability, cybersecurity, liability, and the integrity of navigational information systems. Nevertheless, the fundamental allocation of responsibilities between coastal States and flag States largely remains preserved, despite becoming increasingly dependent upon interconnected digital infrastructure and technical governance mechanisms.

Accordingly, the contemporary international regulatory framework governing AtoN may be understood as a multilayered system based upon the interaction between technologically neutral treaty law and adaptive technical standards. Such interaction enables the modernization of navigational safety systems while simultaneously preserving the stability and continuity of the fundamental principles of international maritime law. Future regulatory development will therefore likely depend not upon redefining the legal concept of AtoN itself, but upon further harmonizing technical governance mechanisms within an increasingly digital navigational environment.

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Workforce Development for Hydrogen Ports

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Abstract: Ports are critical gateways in the emerging global hydrogen trade, supporting industrial decarbonisation and net-zero ambitions. As ports transition into hydrogen hubs, workforce readiness emerges as a binding constraint, with skills shortages already evident across clean energy projects. Adopting a human-centred socio-technical perspective, this study examines workforce-readiness challenges, the required knowledge and technical capabilities, and practical strategies for hydrogen port workforce development. The analysis draws on semi-structured interviews with 28 experts across Australia representing ports, industry, government, and training institutions. Findings indicate that ports face systemic workforce constraints, driven by a mismatch between the scale and urgency of upskilling needs and the capacity of the existing training system. Effective workforce development depends on coordinated, multi-actor governance rather than isolated port initiatives. The study concludes that hydrogen port readiness depends not only on infrastructure and technology deployments but on the timely mobilisation of a capable and resilient workforce, positioning workforce development as a strategic asset in the hydrogen economy.

Keywords: port, hydrogen supply chains, workforce development, renewable energy

1. Introduction

As the global hydrogen economy advances towards commercialisation, port readiness emerges as a critical determinant of international hydrogen trade (Chen et al., 2023). Ports are no longer confined to conventional freight-handling functions; they are transitioning to multi-energy modes that support hydrogen production, conversion, storage, transport, and end-use integration. This transformation positions ports as strategic interfaces linking regional renewable energy systems with the global clean fuel market, thereby reinforcing their central role in the energy transition.

Ports across Europe and the Asia Pacific region are leading hydrogen infrastructure development, reflecting strong policy ambitions and industrial capabilities. It is projected that hydrogen throughput at the Port of Rotterdam could reach approximately 20 million tonnes by 2050, supported by expanded ammonia handling capacity and large-scale blue and green hydrogen projects (Pivetta et al., 2024). Similarly, the Port of Antwerp-Bruges host a 100 MW electrolysis plant, participates in the HyTrucks initiative, and is home to the first hydrogen-powered tugboat (Li et al., 2025). In Southeast Asia, the Port of Singapore has diversified its multi-fuel bunkering strategy to include ammonia and methanol and is exploring ammonia-fired power generation (IEA, 2025). Kobe and Hastings have executed the first liquefied hydrogen shipment (Chen et al., 2023), while Qingdao operates a comprehensive hydrogen-energy port with hydrogen-powered vehicles and hybrid tugboats (Li et al., 2025).

Concurrently, ports increasingly invest in multi-molecular terminals capable of handling hydrogen, ammonia, methanol, and LNG, enabling operational flexibility amid technological uncertainty (IEA, 2025). Ports also strengthen sector coupling by integrating hydrogen production with offshore wind, transport systems, aquaculture, and adjacent industrial clusters (Pivetta et al., 2024). However, as infrastructure technology advances rapidly, workforce readiness is an increasingly binding constraint on hydrogen port development (Chen et al., 2024).

Workforce capability and the availability of skilled labour are explicitly identified as potential bottlenecks to the expansion of the hydrogen industry (Beasy et al., 2023). Skills shortages are already evident across clean energy construction and operations, underscoring the need for strategic and proactive labour policies to prevent

delays in energy system transformation (McHenry, Krishnan and Tuck, 2024). The integration of hydrogen and renewable energy fundamentally reshapes port job profiles, introducing new technical, safety, and digital competencies. Therefore, workforce capability development to safely and effectively handle hydrogen and its derivatives in the ports represents a critical challenge for port authorities and operators.

This study addresses this challenge by adopting a human-centred socio-technical perspective to propose a workforce development strategy for future hydrogen port operations, contributing to sustainable port development and net-zero objectives. The paper is structured as follows. Following this introduction section, Section 2 reviews the relevant literature, Section 3 outlines the research methods, Section 4 presents the results, and Section 5 concludes this paper.

2. Literature Review

Hydrogen introduces distinct operational and safety challenges for the maritime sector, primarily due to its physical and chemical properties (Hoecke et al., 2021). Integrating hydrogen and derivatives into the existing port environment increases the complexity of routine operations, emergency preparedness, and crisis management. As ports continue to handle legacy commodities alongside emerging hydrogen carriers, operational risk management becomes increasingly multifaceted, requiring workforce capabilities that extend beyond conventional port operations (Chen et al., 2023).

Hydrogen port management requires highly specialised technical, safety, and engineering expertise. Hydrogen's low viscosity and high flammability, as well as ammonia and methanol's toxicity and corrosivity, pose severe risks to occupational health and environmental protection (Hoecke et al., 2021). These characteristics reframe port safety from an operational issue to a strategic workforce capability challenge.

Beyond safety, the hydrogen transition is reshaping workforce demand across multiple dimensions. The broader green energy transitions literature consistently highlights the generation of new employment opportunities and the intensification of skills requirements, particularly across hydrogen supply chains, alternative fuels, and green digital shipping corridors (Kordi et al., 2025). However, empirical evidence indicates that workforce readiness has not progressed at the same pace as infrastructure and technology deployment, exposing a structural skills gap in hydrogen port development (Chen et al., 2024).

Port's workforce development literature identifies recurring themes including safety and risk management, workforce sustainability, operational efficiency, digital transformation, and climate resilience. Safety literature emphasises that human error remains a primary source of disruption in hazardous cargo-handling environments (Khan et al., 2022), prompting growing expectations for ports to deploy automated, risk-aware systems alongside continuous safety training. Workforce sustainability research highlights the importance of human-centred management approaches, demonstrating that organisational support and work-life balance strongly influence talent retention and long-term workforce stability (Bucak, Mollaoğlu and Dinçer, 2023; Vo, Lavissière and Lavissière, 2023). These pressures expand workforce development beyond technical training to include adaptability, resilience, and systems thinking.

The operational efficiency literature highlights the growing interdependence among workforce satisfaction, digital tools, and performance outcomes. Applications such as IoT systems, service-level agreements, and forecasting tools enable ports to anticipate labour demand better and align recruitment with operational needs (Peoples, Moore and Georgalas, 2022). However, digital transformation studies identify workforce capability gaps as a central barrier to the deployment of smart ports and critical energy infrastructure (Daniel et al., 2025). Uncertainty around return on investment, fragmented governance, and insufficient coordination between government and industry constrain the effective development of digital and hydrogen systems (Daniel et al., 2025; González-Cancelas et al., 2025; Potter, Wang and Naim, 2025), reinforcing the need for holistic transformation frameworks that integrate digitalisation, cybersecurity, and workforce training through coordinated multistakeholder efforts. Overall, the literature indicates that while hydrogen infrastructure technologies are increasingly available, ports lack the trained workforce and practical competency standards required to deploy these systems at scale.

Workforce development thus emerges not as a secondary consideration, but as a strategic constraint on hydrogen port readiness. To address this gap, this study is guided by the following research questions:

- RQ1: What workforce challenges do ports face in transitioning toward hydrogen operations?

- RQ2: What training and skill sets are required to support this transition?
- RQ3: What workforce development strategies can ports adopt to address these challenges effectively?

The following section outlines the methodology employed to address these research questions.

3. Methodology

This study employs a qualitative research design, based on semi-structured interviews, to examine workforce development challenges and the required skill set for port transition into the hydrogen economy. This approach reflects the view that reality is socially constructed and best understood through participants' experiences, with semi-structured interviews enabling in-depth exploration of complex and emerging practices (Mason, 2004).

Interviews were conducted via Microsoft Teams between August 2024 and November 2024, with one additional interview in March 2025. A total of 28 experts participated, representing six Australian States (Queensland, New South Wales, Victoria, Tasmania, South Australia, and Western Australia) and the Northern Territory. Participants include nine port representatives (PC), five government representatives (GO), 13 proponents' representatives (HP), and one representative from a training institution (O). Overall, participants reported an average of 23.6 years of professional experience, ensuring a high level of domain expertise.

Most participants transitioned from the oil and gas sector into green hydrogen following its recognition as a key decarbonisation pathway post-2019. Approximately 67 % reported over 20 years of oil and gas experience, providing relevant transferable expertise in safety, risk management, and large-scale energy infrastructure. In terms of roles, 57% occupied senior leadership positions, including General Manager, Chief Technical Officer, or equivalent executive roles, strengthening the strategic relevance of the findings.

Data were analysed using deductive thematic analysis, reflecting the theory-informed and targeted nature of the research question. Deductive analysis enables systematic examination of predefined conceptual themes while maintaining alignment with existing literature and the study's analytical framework. Data saturation was defined as the point at which data sufficiently illustrate predefined conceptual categories; for low-prevalence codes, up to 24 interviews may be required (Hennink, Kaiser and Marconi, 2016). With 28 interviews, this study exceeds the established benchmark. To enhance analytical robustness, interview findings are triangulated with the literature on hydrogen ports. This triangulation strengthens credibility by testing empirical patterns against established evidence and identifying convergences and gaps between theory and practice.

4. Workforce Development for Ports Navigating the Hydrogen Economy

The thematic findings are organised in line with the research questions, addressing workforce development challenges, required skills and training needs, and proposed workforce development strategies.

4.1. Workforce Challenges

The findings of this study demonstrate that workforce constraints pose a material risk to ports' capacity to scale hydrogen operations. These constraints are systemic and interrelated, extending beyond technical training to encompass institutional capacity, labour market dynamics, and organisational readiness. Table 1 synthesises the key workforce challenges identified across stakeholder interviews and the literature.

The findings show a systemic mismatch between the urgency of upskilling and/or reskilling and the capacity of the existing workforce system. Upskilling refers to deepening or augmenting specialised knowledge to meet the demands of the hydrogen commodity (Beasy et al., 2023), such as load masters handling liquid hydrogen carriers. In contrast, reskilling (retraining) involves preparing workers for entirely new roles or industries, particularly when existing jobs are threatened by industry shifts (McHenry, Krishnan and Tuck, 2024), such as a coal conveyor technician transitioning to a wind turbine technician. Shortages of critical operational personnel, particularly marine pilots and tugboat crews required to ensure the safe passage of hydrogen and derivative carriers, are already constraining operational readiness and are likely to intensify without early intervention (HP13). This concern is reflected by participant O1, who emphasised: "*We need a workforce with the knowledge to support the growth of the Pilbara as a hydrogen hub or as an importer of renewables to offset carbon emissions. This is crucial for the region's development and its role in the hydrogen economy.*"

Table 1. Workforce Challenges for Hydrogen Ports

Theme	Empirical findings	Literature Review Insights
Scale and speed of workforce transition	Acute shortages in marine services roles, intensified with competition from mining sectors (GO5); lack of early planning expected to exacerbate shortages (GO4)	Industry recognises the need for workforce development but reports insufficient training capacity and expertise to support the hydrogen sector's growth and (re)skilling needs (Beasy et al., 2023; MJTTF, 2024).
Hydrogen-specific technical skills gap	Limited competencies in hydrogen production, storage, refuelling, and materials handling; products of specific hazards dominate workforce concerns (HP1, HP2, HP5, PC2, PC6, PC7)	Safety, familiarity, and technical competence are central barriers to alternative fuel adoption (Chen et al., 2024; Kim, Lee and Lim, 2025)
Safety and emergency preparedness	Existing emergency response plans are not calibrated to hydrogen scenarios; early coordination with the hospital and emergency services is required (GO1, PC1)	Hydrogen operation requires dedicated emergency protocols and inter-agency coordination (Beasy et al., 2023; McHenry, Krishnan and Tuck, 2024)
Shortage of expertise and trainers	Workforce largely drawn from oil and gas sectors requires upskilling; limited availability of hydrogen-experienced trainers and hands-on training facilities (PC1, PC2, PC3, HP13)	Widespread shortage of experienced personnel capable of delivering practical hydrogen training (Beasy et al., 2023; Chen et al., 2024).
Institutional and regulatory lag	Accreditation, certification, and standards lag technological development, resulting in workforce-operation misalignment (GO1, HP9)	Qualification and accreditation frameworks are not keeping pace; national training packages have not yet included hydrogen (Beasy et al., 2023; Chen et al., 2024)
Recruitment, demographics, and retention	Persistent labour constraints in regional and remote sites; Indigenous consent processes increase expectations for local training and employment outcomes (HP2)	Competition for technical talent, ageing workforce, gender imbalance, and limited work–life flexibility undermine long-term workforce sustainability (Li and Miller-Hooks, 2023)
Cost for upskilling	Unclear cost responsibility for workforce upskilling (O1)	Lack of funding remains a major barrier, driven by uncertainty over the commercial returns of emerging hydrogen technology (Beasy et al., 2023; Daniel et al., 2025)

Emergency preparedness for potential hydrogen-related risks remains underdeveloped, as aligning port operations with hydrogen risk profiles requires deeper coordination with health and emergency services, especially in remote locations (GO1). At the operational level, persistent skills gaps in hydrogen handling, cryogenic systems, and product-specific hazards highlight deficiencies not yet embedded in mainstream port training (Chen et al., 2024). These challenges are compounded by the limited availability of hydrogen-specific expertise, delays in accreditation and standards development and fragmented ownership of technical knowledge. Recruitment and retention further undermine workforce sustainability as ports compete with higher-paying sectors for technical and digital talent (Potter, Wang and Naim, 2025).

Empirical findings are consistent with the literature. The human element often acts as a disruptor to technology adoption, including resistance arising from fear of job loss due to automation(González-Cancelas et al., 2025). Further uncertainty surrounds the cost responsibility for workforce upskilling. The transition is also

constrained by unresolved questions of cost responsibility for upskilling, as articulated by O1, who noted the absence of clear ownership for workforce investment. Overall, the findings demonstrate that hydrogen port development depends not only on technical upskilling but also on coordinated institutional commitment and strengthened workforce adaptive capacity to manage uncertainty, risks, and rapid technological change.

4.2. Training and Skillset Requirements

This study identifies a multilayered set of training and skill requirements underpinning hydrogen port readiness. Table 2 presents the interview findings, categorised into eight themes.

Table 2. Training and Skillset Requirements

Theme	Empirical Findings	Literature Findings
Operational handling of hydrogen and derivatives	Training on hydrogen properties (flammability, leak propensity); hazard identification (cryogenic risks) (HP1, HP4-HP6, HP11-HP13, PC5-PC9)	Competence in physical and chemical properties and standardise port risk assessment for safe handling of hydrogen derivatives (Chen et al., 2024)
Emergency preparedness and response	Scenario-based and functional testing of emergency plans, evacuation planning, and first responders training (GO1, GO5, HP8, HP12, PC1, PC9)	Upgrading ports' emergency management systems to align with the global procedures for managing major incidents (Khan et al., 2022)
Engineering and technical design skills	Capability to design, retrofit, assure, test, and inspect hydrogen port infrastructure; management of regulatory change (GO3, HP11, HP12, O1)	Engineering demand outpaces supply; key roles include process safety, mechanical, and electrical engineers (McHenry, Krishnan and Tuck, 2024)
Marine operations	Hydrogen and derivatives loading, stevedoring, pilotage, tug operations, bulk terminal handling, and equipment inspections (GO1, GO3, GO5, HP12, HP13, PC1, PC6-PC9)	Port-specific training, typically adapted from seafarer training, requires updating to address new fuel systems, bunkering safety zones, and abnormal conditions (MJTTF, 2024)
Digital, assurance, and traceability	Assurance testing, monitoring systems, sustainability reporting, and hydrogen traceability across the supply chain (GO3)	Energy transition intersects with digital shipping, requiring skills in cybersecurity and data analytics (Daniel et al., 2025)
Project and construction phase training alignment	Training developed alongside project definition; execution-phase-specific training rather than premature standardisation; learning from LNG project delivery (GO1, GO5, HP11, PC3, PC5, PC7)	Construction labour demands include specialised trades and inspectors critical to infrastructure delivery (McHenry, Krishnan and Tuck, 2024)
Automotive	Operation and maintenance of hydrogen-fuelled trucks, refuelling stations, and hydrogen forklifts (PC2, PC7-PC9)	Decarbonising port assets requires hydrogen-based vehicles and refuelling infrastructure, increasing operators' skills requirements (Chen et al., 2024)

Workforce capability requirements span operational handling, emergency preparedness, engineering design, marine operations, digital assurance, and construction phase delivery. These requirements reflect both the distinct physical and safety characteristics of hydrogen and derivatives and the broader transformation of ports into integrated, digitally enabled hydrogen hubs. Importantly, training needs are dynamic and evolve with project maturity (PC3), requiring alignment between learning activities and project execution stages rather than reliance on premature standardisation. The breadth and interdependence of these skill categories indicate that hydrogen port readiness cannot be achieved through isolated training interventions but requires a coordinated workforce strategy that integrates technical competencies, safety governance, project-based learning, and long-

term capability development across port ecosystems, which provides a foundation for the workforce development strategies outlined in the following section.

4.3. Workforce Development Strategy

The findings show that workforce development strategies for hydrogen ports vary systematically across ports, government, and project proponents, reflecting distinct economic, environmental, social governance (ESG), and technical logics. These strategies are complementary rather than substitutive, indicating that hydrogen port readiness depends on coordinated, multi-actor intervention rather than isolated port action. The consolidated strategies are presented in Table 3.

Table 3. Workforce Development Strategies for Hydrogen Ports by Actor

	Ports	Government	Proponents (Industry)
Economic	• Leverage transferable skills from the oil and gas industry (PC3, PC5) • Form a public-private partnership to leverage private sector investment and expertise for training facilitation (Chen et al., 2024)	• Invest in public training infrastructure (hydrogen skills centre, innovation hubs) (PC4, HP7) • Support strategic fleet and sea time initiatives to address marine labour shortages (GO5) • Provide financial instruments to support workforce transition (O1, Beasy et al., 2023)	• Use active projects as cost-effective training platforms (GO4) • Engage experienced third-party contractors to transfer knowledge and reduce start-up risks (PC5)
ESG	• Coordinate emergency preparedness with the emergency hospital and first responders (GO1) • Support workforce adaptability and acceptance of new technologies and regulatory compliance (GO4, HP5,Chen et al., 2024) • Adopt human-centred management practices, including work-family balance initiatives and monitoring social satisfaction (Peoples, Moore and Georgalas, 2022)	• Build long-term workforce pipelines through STEM education and early engagement (O1, PC6) • Reduce reliance on migration by developing domestic skills (O1) • Clear training pathways, standardise accreditation, certification, and national framework to reflect hydrogen and derivatives (GO1, Beasy et al., 2023)	• Embed indigenous training and employment commitment within project consent, particularly in remote regions (HP2) • Promote staff exchange and knowledge sharing (HP11)
Technical	• Implement competency-based, hazard-specific training aligned with the port safety management system (GO1) • Differentiate training by commodity characteristics (PC5, PC7) • Prioritise the adoption of smart port technologies to provide simulation environments where workers can practice high-risk tasks safely (Daniel et al., 2025)	• Enable rapid technical upskilling through a micro-credentials module delivered via vocational schools (GO2) • Support hydrogen-specific training for automotive, refuelling, and marine services (GO2)	• Design technology-specific commodity training (HP5) • Train workforce through a commercial-scale testing environment (HP7)

Workforce development strategies require clear role differentiation across actors. Government strategies focus on system-level capacity building through expansion of micro-credentials (GO2), strengthening the STEM education pipeline via collaboration with educational institutions (GO4, GO5, O1), developing national competency frameworks for the hydrogen commodity (GO1), and implementing targeted initiatives to address maritime skills shortages, such as strategic fleet programs for pilots and seafarers (GO5).

Ports adopt operationally grounded strategies, prioritising skills transfer from oil and gas (PC3, PC4), early collaboration with proponents to co-design fit-for-purpose training (HP5), alignment of training intensity with project development phases (HP5), and the selective use of international expertise to accelerate operational readiness (HP10, HP13). Ports also emphasise investment in hydrogen-specific emergency response capability and in transforming safety culture (PC1, PC8), advocating a tiered, role-based training structure aligned with specific commodities to avoid overtraining and ineffective resource allocation (PC7). Proponents leverage active projects as practical training environments (GO4), engage experienced third-party contractors for knowledge transfer (PC5), and utilise commercial-scale testing to accelerate workforce competence (HP7). Indigenous training and employment commitments are embedded within project consent processes, particularly in remote regions (HP2), reinforcing social license and long-term workforce sustainability.

Proactive workforce planning aligned with evolving port roles is critical. Participant O1 cautioned that without early investment, coordinated workforce planning, and firm decarbonisation commitments, hydrogen projects risk stalling due to labour constraints. Overall, the findings demonstrate that workforce development for hydrogen ports constitutes a distributed governance challenge, requiring aligned economic incentives, social legitimacy, technical robustness, and regulatory coordination to ensure the long-term sustainability of hydrogen port systems.

5. Conclusion

This study examines workforce development as a key enabler of ports' transition to hydrogen operations, addressing interrelated research questions on workforce challenges, capability requirements, and strategic responses. The findings indicate that Australian ports face workforce constraints in engaging with hydrogen supply chains, characterised by a mismatch between the scale and urgency of upskilling needs and the capacity of existing training systems. Persistent gaps in hydrogen-specific technical skills, safety, and emergency competencies, institutional and regulatory lags, and labour market pressures arising from competition with the mining sector collectively challenge hydrogen port readiness. These challenges are compounded by socio-technical resistance to change and unclear responsibility for funding workforce transition.

Hydrogen port readiness requires a multilayered skill set spanning operational handling of hydrogen and its derivatives, emergency preparedness, engineering design and retrofit capability, marine and logistics operations, and digital assurance and traceability. These competencies are commodity-specific and risk-differentiated, particularly for ammonia and hydrogen, and should evolve in parallel with project maturity. Accordingly, the training system should move beyond generic upskilling towards competency-based frameworks, structured refresher programmes, and project-embedded learning within operational environments.

Effective workforce development depends on coordinated, multi-actor strategies rather than isolated port initiatives. Ports, governments, industry bodies, proponents, and education and training organisations should collaborate to enhance awareness of safety issues related to H2 and its derivatives. Several recommendations arise from this study's findings. Industry bodies and governments should accelerate accreditation reform, broaden the use of micro-credentials, and invest in dedicated hydrogen training infrastructure aligned with port requirements. Ports and proponents need to embed training within projects to support practical skills development and accelerate knowledge transfer. National competency frameworks should standardise skills while allowing for commodity-specific differentiation. Funding responsibilities should be clarified through public-private mechanisms to ensure timely mobilisation of skills.

Maritime Education and Training (MET) institutions play a crucial role as intermediaries between policy and industry. Their role includes developing accredited hydrogen-focused curricula that incorporate safety and emergency response modules and embed digital competencies. Strengthening MET capacity and industry engagement is essential to hydrogen port readiness.

Workforce development for hydrogen ports constitutes a distributed governance challenge, requiring alignment across economic, social, technical, and institutional dimensions. While this research focuses on Australian ports, the identified workforce capability needs are broadly relevant globally. Hydrogen port readiness depends not only on infrastructure and technology deployments but on the timely mobilisation of a capable and resilient workforce. By positioning workforce development as a strategic asset, this study provides

actionable insights for ports, policymakers, and industry actors navigating the hydrogen economy. Future research should further differentiate workforce needs across hydrogen and derivatives pathways.

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