SHARJAH MARITIME ACADEMY أكاديمية الشارقة للنقل البحري

Proceedings of the 1st International Maritime Education, Training, and Research Conference

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17-18 February 2025

Editors:
Prof. Dr. Emma Northam
Dr. Serdar Yildiz

PROCEEDINGS

***International Maritime Education, Training and Research Conference*, Sharjah Maritime Academy, Khorfakkan, Sharjah, 17-18 February 2025**

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Chancellor's Note

It is with immense pride and deep appreciation that I welcome you to the Proceedings of the 1st International Maritime Education, Training, and Research Conference, held on 17 and 18 February 2025 at Sharjah Maritime Academy (SMA), Khorfakkan, Sharjah United Arab Emirates (UAE). This milestone event marks a significant chapter in our Academy's journey to become a maritime hub for thought leadership, innovation, and collaboration in maritime governance, education and research.

The conference brought together more than 200 participants, representing over 30 nationalities and 20 distinguished organizations spanning academia, industry, regulatory authorities, and maritime enforcement bodies. This diverse and dynamic engagement underscores the growing recognition that global maritime challenges demand integrated, multistakeholder solutions. Active participation and high level contributions from all sectors validated the SMA's vision; the future of maritime safety, sustainability, and innovation can only be achieved through the synergy and collaboration between academic institutions, maritime industry stakeholders, and regulatory bodies.

Through the two day program, participants engaged in transformative topics critical to the maritime domain, including autonomous shipping, safety assurance, proactive risk management, green energy transitions, fuel cell technologies, and advanced fire safety designs. Each paper and panel discussion reflected the SMA's commitment to the United Nations Sustainable Development Goals (UN SDGs) and the UAE's National sustainability agenda, particularly in areas such as quality education (SDG 4), industry innovation (SDG 9), sustainable cities and communities (SDG 11), climate action (SDG 13), and partnerships for the goals (SDG 17).

The emergence of Maritime Autonomous Surface Ships (MASS), alternative fuels and energy sources, new technologies, smart ship operations, and AI-driven safety systems signals not only a technological revolution but also a call to action for maritime education and workforce transformation. As highlighted during the conference, we must prepare current and future seafarers for these shifts through reimagined training frameworks and research-driven policy dialogue. In parallel, decarbonization efforts and the transition toward net-zero shipping reaffirm the importance of learning from our maritime heritage while embracing bold innovation and infrastructure development.

SMA is honored to have served as the convening platform for this forward-looking dialogue. Our goal was to create an inclusive space that fosters cross-disciplinary exchange, bridges the gap between policy and practice, and catalyzes solutions that will shape the maritime world of tomorrow. I extend my sincere gratitude to our speakers, researchers, partners, and organizing teams who made this event a success.

Let these proceedings serve not only as a record of academic excellence but also as a call to deepen our cooperation across sectors and borders. Together, let us navigate the path forward, safely, sustainably, and inclusively.

Dr. Hashim Alzaabi
Chancellor
Sharjah Maritime Academy

Provost and Vice Chancellor's Note

It gives me great pleasure to introduce the proceedings of the First International Maritime Education, Training, and Research Conference held at Sharjah Maritime Academy in February 2025. This landmark event marked a significant milestone for our young but ambitious institution, placing SMA firmly on the map of global maritime research.

Over two days, internationally renowned academics and leading industry professionals came together to share cutting-edge research, discuss sectoral priorities, and debate pressing issues such as maritime safety, sustainability, and automation. The conversations were stimulating, bridging the gap between scholarship and practice. Industry colleagues gained valuable insight into the latest academic findings, while researchers benefitted from hearing first-hand about the challenges faced by practitioners in the field. This reciprocal engagement exemplifies the Academy's vision and mission to bridge the worlds of scholarship and industry in addressing the most pressing challenges of our time.

Our students played a full part in this academic exchange. They engaged with delegates throughout, and on the second day proudly presented their own research projects, a testament to the promise of the next generation of maritime professionals and scholars.

As Provost, I was honored to preside over the sessions and witness the spirit of intellectual curiosity and collaboration that defined this inaugural conference. I am confident that it has laid the foundation for many future dialogues, research partnerships, and innovations that will shape the future of the maritime sector, and to host an even bigger event in the next year.

I extend my sincere appreciation to all contributors, delegates, and partners whose expertise and commitment made this conference a success. These proceedings stand not only as a record of academic excellence but also as a beacon for the collective pursuit of knowledge and innovation that will shape the maritime world of tomorrow.

Prof. Capt. Syamantak Bhattacharya
Provost and Vice Chancellor Academics
Sharjah Maritime Academy

Navigating the Future of Maritime Industry: Insights from the First International Maritime Education, Training, and Research Conference

Against a rapidly evolving backdrop of technological advancement and global challenge, the maritime industry faces a period of unprecedent transition. The papers presented at Sharjah Maritime Academy's first International Maritime Education, Training and Research Conference capture the breadth of current research, innovation, and discourse shaping the future of maritime education, operations, energy solutions, and safety frameworks.

One of the most profound shifts in the industry is the rise of remotely controlled and autonomous shipping, demanding significant changes in policy and strategic planning. The reach of these changes is captured in the papers by Schröder-Hinrichs et al. and Karolius. The first focuses on the need for maritime education and training to adapt in order to effectively prepare maritime professionals for careers in the digital age of shipping. The second explores the challenge of ensuring, and being able to verify, that the safety performance of autonomous systems matches – or exceeds – that of human operators. Both papers reflect the growing sense of urgency around the risk posed by widening gaps between technological advance and the educational and regulatory frameworks, and their potential to impact global disparity in preparedness and workforce safety.

The critical theme of safety continues through the contributions from Yildiz, Paterson, and Salem. Yildiz examines the shift toward predictive safety models, integrating human factors and dynamic risk assessments to support proactive decision-making. Paterson's research into innovative materials aims to reduce the potential for loss of life in the event of flooding in both new and, importantly, older ships, and Salem's work advocates the adoption of risk-based fire safety design principles for modern cruise ships. Collectively, these papers emphasize the vital role of multidisciplinary approaches to addressing the maritime industry's longest-standing challenge – safeguarding crews, passengers, cargos and vessels.

The multidisciplinary efforts required to address one of the industry's more recently recognized challenges – sustainability – are also apparent in the paper from Rawashdea and Kawansson and focusing on innovations in proton-exchange membrane fuel cells that could pave the way for cleaner fuel alternatives. The thread of urgency and the requirement to combine a wide range of disciplines and expertise to keep pace with the changes faced by the maritime industry and ensure the safety, sustainability and future of its global workforce and the marine environments they work in, are drawn together in Wright's contribution. Examining the motivators and process of the transition from sail to steam over the course of a century, the paper explores what we can learn for the transition to net zero that must be achieved in less than a quarter of that time.

The Conference brought together international experts from academia, higher education and industry with our staff and students at the Sharjah Maritime Academy. Its aim was to build and strengthen the bridge between research, and the development of new knowledge and solutions to the challenges the maritime industry, and those who work in it, face every day. The breadth of contributions reflects this aim and captures the need for collective discussion and action to build a resilient, forward-thinking maritime future.

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Table of Contents

1. The Role of Training and Education in Remotely Controlled and Autonomous Shipping

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Abstract

Shipping, the indispensable mode of transport which enabled globalization, is undergoing fundamental changes because of the further introduction of automation and technology as part of the Fourth Industrial Revolution. These are culminating in Maritime Autonomous Surface Ships (MASS) and Smart Ships on the way to higher levels of autonomous operation. The underlying discussions focus on the timelines for implementation of these new types of ships and the impact they will have on the maritime workforce. There are several factors that need to be aligned for the introduction of new technologies, as shown by the so-called Technology Adoption Model (TechAdo). This model was developed specifically to assess such developments and identifies, among other elements, human capital as a critical factor in the adoption of new technologies in any industry. This relates to the availability of a trained and qualified workforce and raises the question of the education and training required to prepare the next generation of seafarers or to retrain and up-skill existing seafarers for the operation of MASS and Smart Ships. This paper discusses the educational needs and potential career paths in a digital age of seafaring and highlights potential challenges that need to be addressed for a successful transition of the shipping sector to higher levels of automation.

Keywords: MASS; Smart Ships; maritime education and training; competency development; technology adoption; TechAdo; future shipping

1. Introduction

The ripple effects of the Fourth Industrial Revolution introduce new levels of automation and digitalization to the maritime sector and have enabled the development of Maritime Autonomous Surface Ships (MASS) and Smart Ships. The transformation of global shipping through remotely controlled and autonomous vessels aligns with decarbonization efforts and predictive maintenance paradigms, reducing Greenhouse Gas (GHG) emissions, optimizing fuel efficiency and minimizing human error-induced maritime accidents. The International Maritime Organization (IMO) is actively shaping the legal, technical and ethical frameworks required to facilitate the adoption of these cutting-edge innovations.

Small size autonomous or remotely operated vehicles are already in use for some time in the scientific exploration of the oceans to measure, among others, currents, temperatures and other relevant data. However, industry efforts to use the experiences gathered in operating these small-scale units took automation in shipping to a new level when Rolls Royce and Finferries created what they called the first autonomous car ferry in Finland at the end of 2018. At the same time, announcements were made in Norway to create a fully autonomous ship, "Yara Birkeland" (Yara 2021), which triggered substantial discussions about the fate of seafarers and their professional career perspectives in such an automized world.

Autonomous ships were promoted as a means to eliminate the "human factor", the main source of unsafe acts leading to accidents in shipping and thus creating a significantly safer industry. A study undertaken by the World Maritime University (2019) systematically reviewed the effects of automation as well as the introduction of new technologies and further levels of automation in transportation, including shipping, in order to assess the consequences of such a development for the maritime labor force. The study concluded, among others, that the speed of introduction of higher levels of autonomy in the shipping sector would not be disruptive and instead autonomous ships would be introduced gradually. Therefore, seafarers would still be needed and thus the study did not forecast a declining demand for seafarers - at least not until 2040. The study identified missing financial benefits, as well as missing regulations and governance as the most important hurdles for autonomous ships being introduced to the sector.

Even though the number of autonomous ships to be deployed in a near future is expected to be small and confined to national jurisdictions, IMO has taken a proactive role by starting to review its existing regulations. Through the work of its Maritime Safety Committee (MSC), Legal Committee (LEG) and Facilitation Committee (FAL), IMO has identified gaps and challenges in adapting global shipping laws to autonomous technology and in particular MASS at varying degrees of autonomy.

The uptake of MASS depends on resolving these fundamental issues while simultaneously developing a comprehensive understanding of the actual risk profiles and operational capabilities of MASS. This objective necessitates rigorous risk assessment, real-world validation and adaptive regulatory frameworks. Trials in different parts of the world, e.g., China (Chen et al. 2023), Japan (Nippon Foundation n.d.) and South Korea (Jo & Yim 2025) along with the commercial deployment of the "Yara Birkeland" (still under human supervision) in Norway indicate that the technical feasibility of MASS is making solid progress.

Substantial research has been completed on deep learning algorithms, sensor fusion and edge computing to facilitate real-time navigation, docking and performance optimization with minimal or no direct human intervention (Thombre et al 2020). At a first glance, these autonomous systems may appear to function independently. However, in real-life operational environments, human oversight remains a critical component of system resilience and fault tolerance, particularly in unstructured scenarios with emerging failures or unpredictable marine environmental conditions where automation may encounter their decision-making limitations. This requires a workforce with specialized competencies in autonomous system diagnostics, cybersecurity and AI-driven decision augmentation. Operators must possess the cognitive adaptability to rapidly interpret and intervene in complex and high stakes scenarios and must quickly develop an understanding of the system's internal logic and algorithmic pathways, commonly referred to as the black box phenomenon in AI systems. As a result, the competency requirements for personnel overseeing and interfacing with autonomous vessels could be significantly elevated.

The aspects of the changed requirements for human supervision of MASS are only one example but highlight the importance of training and education. This leads to questions about required training schemes and education programs needed to support the deployment of MASS.

This paper is therefore looking especially into the qualification and training needs and discusses how Maritime Education and Training (MET) needs to adapt to the new world of shipping in order to provide for the required qualifications to operate MASS. Furthermore, a brief discussion should be undertaken about the challenges for different regions in the world to provide the necessary training for MASS related services.

2. The enablers of autonomous shipping

For the uptake of a specific technology, different factors have to come together. The Technology Adoption (TechAdo) Model (Fonseca et al. 2021) considers six factors for technological diffusion. While technical feasibility and economic benefits may be the starting point for a technology to develop, it also requires a qualified and experienced workforce, the human capital, to allow for this new technology to be introduced into the market. In this respect, technology is complemented by human capital even though certain other labor groups may be substituted. However, only the enabling environment, including social acceptance, governance and regulation, will allow an invention to become a marketable innovation. The adoption of MASS is therefore the product of this whole range of factors and the way they interact with each other. The TechAdo model shown in Figure 1 below clearly portrays that for MASS to become widespread, not only the business case needs to be there with the right technology, but also the right human capital needs to be in place along the MASS value chain.

Earlier studies in relation to emerging MASS and related issues focused predominantly on technical feasibility and economic benefits of MASS (e.g. Mannov et al. 2019). A comprehensive overview about research and development for the different technological components of MASS is provided, e.g., in Kim & Schröder-Hinrichs (2021).

In relation to business models, Fonseca et al. (2021) confirm that there is currently only limited interest amongst ship owners to invest in MASS. The economic benefits resulting from MASS are less obvious for the "traditional" ship owner community. In this context, it should be recalled that "Yara Birkeland" was developed by an entity which did not own ships before and developed this ship as a substitute to road transport for environmental protection related motives. Maybe this is an indicator for the disruptive nature of change that MASS could create to the shipping industry when they introduce a new group of shipowners to the sector. For the time being, while traditional shipowners may not feel confident in purchasing MASS, they are interested in the building blocks that may lead to MASS. This could confirm that, while MASS are still at a conceptual phase, Smart Ships on the basis of MASS technology may enter the shipping sector at an earlier stage.

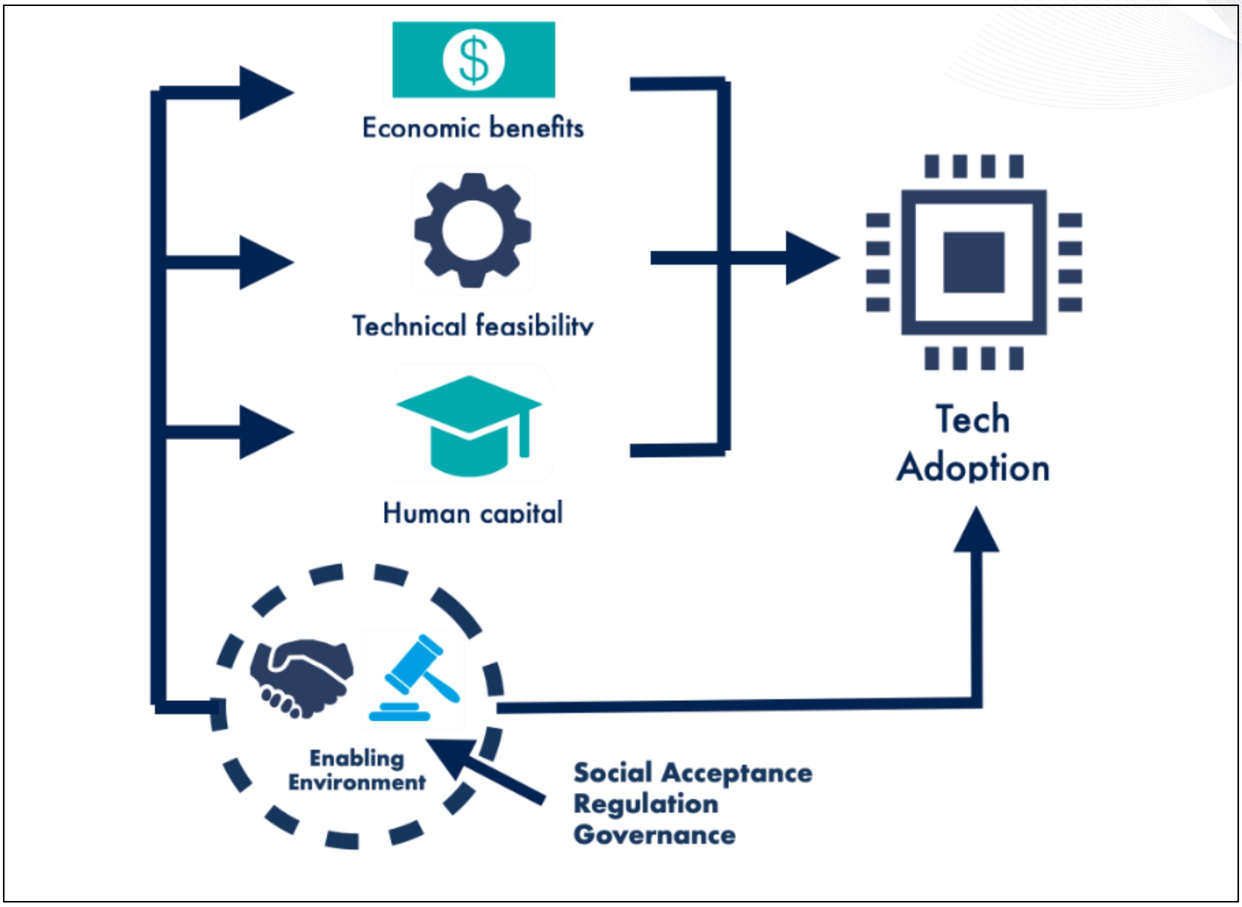

Figure 1. The Technology Adoption (TechAdo) Model (Source: Fonseca et al. 2021)

Kim & Schröder-Hinrichs (2021) also focus on technology governance and refer to the Collingridge Dilemma – the challenge to anticipate social consequences at an early stage of development of a technology – in this respect. The Collingridge Dilemma captures the uncertainty about the impact of MASS on the labor force and the role seafarers could play on MASS quite well. Today, there seem to be consensus that the maritime sector will also rely in the foreseeable future on well qualified seafarers – either on board of Smart Ships or MASS. This underlines the importance of discussing future training and education needs to start preparing the next generation of seafarers for these new ships.

3. Training and education needs for autonomous shipping

MASS rely on a data-driven operational framework with real-time processing of multi-modal sensor inputs, potentially involving LIDAR, RADAR, infrared and satellite-based navigation, which allow to analyze and control the vessel behavior. The ability of human operators to understand and question the validity of AI-driven decision pathways is essential, particularly in scenarios requiring the human operator to override the system decisions due to system uncertainties, unexpected environmental conditions or cyber threats. This is very different from traditional vessel operations, where skill acquisition is rooted in empirical knowledge and hands-on experience of standalone navigation system. Remotely controlled or autonomous ships require human operators to have an advanced understanding of computational models, probabilistic reasoning and AI-derived risk assessments. Such requirements demand a shift from procedural learning to cognitive adaptability, where operators must possess not only operational expertise but also the ability to interrogate and intervene in AI-generated decisions for both navigation systems and engines.

A key challenge in AI-driven maritime autonomy is the backbox nature of machine learning models, where decision logic is often opaque, which makes the fault diagnosis and human intervention challenging. Without the required expertise in algorithmic literacy and system knowledge, intervention is likely to become reactive rather than proactive, which could potentially increase the systemic risk in autonomous maritime operations (Sharma & Kim, 2022). Furthermore, cybersecurity threats pose additional challenges (Kavallieratos, G. & Katsikas, S 2020), as remotely operated or fully autonomous vessels rely on complex networks susceptible to data communication interruptions, adversarial attacks and signal interference. Operators must therefore be trained to anticipate and mitigate cyber-physical vulnerabilities under potential attack vectors.

3.1. International norms for maritime education and training

The issues highlighted above are only a few examples of competence requirements which are not addressed in the existing regulations of the IMO for seafarer training and education. On an international level, seafarer competence requirements are covered by the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW). The Convention was adopted in 1978 following the Torrey Canon accident in 1967. The Convention is updated on a regular basis and included major revisions in 1995 and 2010 following diplomatic conferences. As part of the 1995 amendments the so called STCW Code was introduced. The Code includes the minimum standards of competence for different seafaring professions in a series of tables in the mandatory Part A. Part B of the Code provides recommended guidance for the implementation of the Convention.

IMO embarked on a Regulator Scoping Exercise (RSE) in 2017 to assess how instruments of the Organization could facilitate MASS operations. RSE lists the STCW Convention and its Code as a high priority area for work within the Organization, suggesting that significant effort should be made to provide needed clarifications and guidance before MASS operations at higher levels of autonomy can be conducted at larger scale. The outcome of the RSE is documented in MSC 1/Circ. 1638 (IMO 2021). For the STCW Convention, three main items are listed – (1) definitions and clarifications regarding the meaning of the master (of a ship), the crew and responsible persons, (2) definitions and clarifications regarding Remote Control Stations, and (3) definitions and clarifications regarding Remote Operators designated as seafarers.

For the evaluations undertaken as part of the RSE, IMO introduced four levels of MASS operations where at Degree I and II a crew would still be on board. A Remote Operator would be involved in operations from Level II upward. Level III and IV would involve ships without a crew.

The RSE primarily concentrated on highlighting the need for defining the new roles that ship crews and Remote Operators would play. It also focused on pointing out the need for clarifying the relationship between the Remote Operators and the crew on board. However, the RSE did not identify specific competences to be maintained by crew members or Remote Operators involved in MASS operations. Instead, it is suggested that amendments to the Convention and the Code should be considered when new technologies or automated processes are introduced. While it is important to anticipate and understand how the structure on board and the roles of the different parties will be changing with the introduction of MASS, it is equally important to focus on the competences needed to fill these new roles. This is work that still has to be undertaken.

Maybe, this also indicates the difficulty of defining new training needs, given that the shipping industry still only has very limited experience with MASS in general. The fact that a MASS Code is under preparation which does not envisage such ships to be constructed in large numbers is perhaps another indicator that training for MASS roles may not be needed to a larger extent in the near future.

However, developing new education schemes and programs takes time. Seafarer education is quite special as far as it involves a professional qualification (as defined by the STCW Code) while at the same time it also involves an academic component in many countries where seafarer education is part of the higher education system, not only leading to a professional qualification in form of a Certificate of Competency but also to an academic degree when successfully finishing the academic programs involved. Higher education institutes need clarification in order to amend their academic programs so that relevant education can be offered. As there is a significant time gap between the conceptualization of an academic program and the point from where graduates from these programs enter the labor market, more debates are needed about the content to be covered by relevant academic programs and in which form such training and education should be offered.

As highlighted above, the STCW Convention in its current form does not provide for training content and a training structure that may be needed to operate MASS. There are only a few projects (e.g. the REFRAME project) which have started to focus on defining training content and training needs for operations on MASS and Smart Ships.

3.2. Future skills and competencies for MASS operators

WMU's Transport 2040 project focused during its second phase on future skills and competencies for seafarers in transition. The report (WMU 2023) concluded that future training will be increasingly diversified in terms of training providers and mode of training. Governments and MET institutions will continue to be the main STCW training providers ashore while shipping companies and manufacturers would be able to support on-demand upskilling on board. Online training by specialized training providers with VR/AR and E-learning providers may enhance the learning experience of seafarers to acquire specialized skills in smart and green shipping.

With this diversification of training, lifelong learning will become a key for the upskilling and reskilling of future maritime professionals. This is particularly true because developing critical thinking and analytical skills to determine the value of information for specific problem-solving tasks is important and such soft skills are often not fully developed during formal education. While involved in lifelong learning, seafarers need to be self-guided learners and increase their autonomy and flexibility in designing their own careers. Nevertheless, for the maritime industry to become truly sustainable, it is important that stakeholders, such as shipping companies and the government, support seafarers' lifelong learning with a strategic mindset to increase a pool of talents from young generations, including women and candidates from regions that have so far not fully developed their full potential for seafarer supply.

As autonomous systems become more advanced, the need for traditional seafarers' roles may decrease, but there will most likely still be a human presence on board involved in tasks such as supervision, maintenance, or emergency situations. Training should facilitate the transition of the seafarers to new roles and empower them for oversight tasks rather than active navigation of watch. It is anticipated that autonomous shipping will be a highly complex and interdisciplinary area and this has to be reflected in maritime education and training. Lee and Ahn (2024) identify knowledge and skills in artificial intelligence as well as machine learning as critical areas and advocate for the integration of advanced digital educational platforms and practical training through Education Software as a Service (ESaaS) to increase the flexibility and effectiveness of MET.

The skills listed in the above section illustrate the growing demands of industry on the content of seafarer training. At the same time, these new skills are not listed in the STCW Convention. The recent SkillSea project has therefore identified a growing skills gap between the basic skills required by the STCW Convention and the skills needed to master the digitalized world of shipping. The International Association of Maritime Universities (IAMU) points in a similar direction with its Global Maritime Professional (GMP) initiative. Such an observation is not entirely new. More than 20 years ago, the Thematic Network on Maritime Education and Training (METNET), a project funded by the European Commission from 2000 to 2003, identified similar skills gaps (Schröder et al. 2004). The project developed the so-called 4E model, the first two E's (Essentials and Enrichments) covering the basic requirements of STCW and the additional background required to fully understand these STCW requirements. The project proposed to restructure the approach to MET and address gaps such as the so-called MET Extensions and Elevations, which are offered in addition to the core STCW-related studies. With increasing complexity as a result of further automation and digitalization, it may be time to develop a new 4E model and structure MET accordingly.

4. Career tracks in an age of autonomous shipping

With vessels transitioning from ships with a conventional crew to remotely operated or fully autonomous ships, the role of the ship operators will also shift from direct navigation to supervisory autonomy management. The required expertise extends to algorithmic interpretability, human-autonomy teaming, and crisis intervention, which could be the key training targets.

As the future remotely controlled and autonomous ships will have to co-exist with conventional ships (Kim et al, 2021), the roles of masters and marine engineers will remain critical for operational continuity, safety and regulatory compliance. The heterogeneous nature of global shipping, where autonomous, remotely operated and crewed vessels operate within the same navigational spaces would demand that maritime professionals to possess both traditional seafaring expertise and advanced technical competencies to manage interactions between these diverse vessel types. It is likely that new roles will emerge, such as remote operation operators, AI ship engineers, or maritime cyber security managers to fit with the future demands.

With this, it can be predicted that the integration of AI, automation and remote operations in shipping will redefine many roles in the maritime industry, shifting their career trajectory from traditional hazardous and labor-intensive roles to highly specialized and technology-driven positions. This will enhance the intellectual and strategic depth of maritime careers and improve the welfare and working conditions and elevate their profile to a level comparable to professionals in aerospace, robotics and high-tech industries.

In this regard, traditional seafarer career patterns, characterized by a hierarchical nature (i.e. rank-based) and flexible (i.e. working by voyage contract) (Baum-Talmor and Kitada 2022), are subject to change. Nevertheless, shipboard work organizations are still under review when drafting the new MASS Code.

5. Challenges for the implementation of autonomous shipping

The development of autonomous shipping faces multilayered challenges related to technological, regulatory, and socioeconomic aspects. These elements present a challenging scenario for the maritime industry and all its stakeholders. One key concern is the expanding disparity between nations in the Northern and the Southern Hemispheres. Countries in the Global North are significantly investing in technology-oriented research and the development of autonomous vessels. However, Southern countries, characterized by substantially younger populations, face the risk of lagging behind (WMU 2019), although they would have the potential to reduce shortages in labor market supplies. As a result, the North-South divide in autonomous shipping capabilities is likely to result in a future where prospective seafarers in developing nations encounter reduced employment opportunities. As the demand for conventional seafaring skills declines, the transition to "e-faring" competencies is unlikely to be achievable in the Global South, hence intensifying the economic disparity among maritime nations and widening the gap between the Global North and the South.

The WMU Transport 2040 report provides much more details about the readiness of countries around the world to embrace autonomous shipping (Lagdami & Ballini 2023). Developed countries which possess advanced technology infrastructure and being home to well-established maritime sectors and supportive legislative frameworks will be the early adopters of autonomous shipping. In contrast, underdeveloped nations may encounter difficulties modernizing port infrastructure and educating their workforce for autonomous operations. The disparity in preparation across nations may result in a bifurcated global shipping industry, with some governments and regions more predisposed to adopting autonomy than others.

In addition, while the primarily focus of the work of Maritime Just Transition Task Force was decarbonization, this Task Force sheds light on the challenges of autonomous shipping. The Task Force underlines that technological transitions in shipping must be done in a human-centered manner, with improved collaboration between government, industry, workers, and academia (ICS n.d.). The principles established by the Task Force could be deployed in the same way to ensure the transition to autonomous shipping does not drastically impact the very vulnerable maritime workers and communities that built the maritime industry in the first place.

A coordinated world-wide effort across international organizations, governments, the private sector, and maritime labor leaders is essential to tackle these multifaceted difficulties. The extensive implications of the autonomous shipping sector require careful consideration, and the implementation of technical innovations must be equitably and sustainably balanced for the global maritime ecosystem they will influence. This will need balancing innovation and efficiency with the necessity of maintaining a path towards inclusive economic growth and employment for all regions.

6. Conclusions

The Fourth Industrial Revolution has introduced further levels of automation and digitalization to the maritime sector, leading to the development of MASS and Smart Ships. IMO is actively working on legal, technical, and ethical frameworks to support the integration of autonomous ships. While small autonomous vessels have been used for scientific research, industry leaders have advanced automation in shipping by launching autonomous ferries and cargo ships like the "Yara Birkeland".

Studies indicate that automation in shipping will be introduced gradually, and seafarers will still be needed until a foreseeable future. However, the adoption of MASS depends on the pace of overcoming economic, regulatory, and technological barriers. IMO has begun developing the regulations needed to facilitate the transition. The development of, e.g., deep learning algorithms, sensor fusion, and AI-based navigation has made MASS more technically feasible. However, human oversight remains critical, especially in unpredictable scenarios requiring intervention. This necessitates new competencies in system diagnostics, cybersecurity, and AI-driven decision-making for maritime professionals to name a few examples.

MET must evolve to equip personnel with these advanced skills must and adapt curricula to include AI, cybersecurity, and automation-related training to prepare seafarers for supervisory roles in an increasingly digitalized industry. The STCW Convention currently lacks specific training content for MASS operations, creating an urgent need for revised regulations. Future seafarers must acquire algorithmic literacy and cognitive adaptability to manage AI-driven navigation systems. The maritime industry must also address the global disparity in preparedness, as developing nations risk falling behind in autonomous shipping capabilities. The economic and technological gap between developed and developing nations presents a significant challenge, highlighting the need for inclusive policies and international collaboration. Ultimately, autonomous shipping is poised to redefine maritime careers, improving safety, efficiency, and environmental sustainability, but requires coordinated efforts to ensure a smooth transition for the global workforce.

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2. Bridging the Safety Gap: Addressing the Assurance Challenge of MASS

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Abstract

Recent advancements in sensor technologies, computational power, and artificial intelligence (AI) have generated significant optimism about the future of Maritime Autonomous Surface Ships (MASS). These innovations promise to revolutionize maritime transportation and logistics by enhancing efficiency and safety. However, progress has been slower than initially expected due to substantial technical challenges. The primary challenge lies in ensuring that the safety performance of autonomous systems matches or exceeds that of human operators and verifying this safety level through quantifiable and proven methods. This paper addresses the assurance challenges associated with MASS. Traditional safety assessment methodologies, based on decades of experience, may not suffice for these innovative systems. The paper highlights the potential risk of a safety gap emerging as technology advances without assurance methodologies evolving in the same pace. It emphasizes the importance of updating our assurance processes alongside new technologies, adopting a systems-approach, and using modularization and simulation-based verification to manage the complexity and interdependencies of MASS systems. The paper also discusses the role of Classification Societies in developing technology-specific guidelines and the need for detailed performance requirements over high-level process guidance to fully substantiate safety equivalence. The findings highlight the critical need for further research to develop comprehensive assurance processes that can keep pace with technological advancements in the maritime domain, ensuring that a safety gap does not develop and ultimately making safe MASS a reality.

Keywords: MASS; Autonomy; Assurance; Safety; Technology

1. Introduction

The rapid advancements in technology over the past decades have significantly transformed various transportation industries, including the maritime sector. The emergence of autonomous systems and concepts aims to revolutionize the way goods are transported. This evolution is driven by the third AI summer, which has accelerated Artificial Intelligence (AI) at an immense pace, along with the ever-increasing availability of advanced sensor technology, computational power, and data through the Internet-of-Things (IoT), as well as significant advancements in connectivity and communication. However, progress has been slower than initially expected due to substantial technical challenges, primarily in ensuring that the safety performance of autonomous systems matches or exceeds that of human operators and verifying this safety level through quantifiable and proven methods.

As technology evolves rapidly, it is crucial to establish frameworks and methods to ensure the safety of these innovations, especially for safety-critical applications. Rigorous design review, testing, verification and validation of complex systems are essential for effective risk management. However, there is a concern that our processes and tools for managing risk in the maritime domain may not be evolving at the same pace due to insufficient experience. The rules and requirements for safety assessment are often based on decades of experience, which is lacking for the more recently developed autonomous systems and concepts.

In previous studies by Karolius et al., (2024a) and Løvoll et al., (2024), several assurance challenges associated with these advancements are highlighted. These challenges form the basis for the discussion in this paper, cautioning against the development of a potential safety gap as technology advances without assurance methodologies evolving in the same pace. It highlights the importance of updating our assurance processes alongside new technologies, looking to other industries that rely more on a systems-approach, using modularization, and simulation-based verification to manage the complexity and dependencies of complex MASS systems. The paper also discusses the role of Classification Societies in developing technology-specific guidelines and emphasizes the need for detailed performance requirements over high-level process guidance to fully substantiate safety equivalence. It explores the importance of ensuring safety assurance for these new, innovative, and complex systems, and summarizes key research questions that must be addressed to mitigate this potential emerging safety gap.

2. The assurance challenge

2.1. Technology driven ambitions

Over the years, ships and ship systems have seen significant advancements. The maritime industry has been laying the groundwork for the autonomous revolution for decades, continuously enhancing and introducing new technologies such as IMU, RADAR, ECDIS, AIS, GPS (GNSS), etc. Advanced heading, speed, and track control systems, combined with highly controllable propulsion and steering systems, enable vessels to follow a predefined path using a pre-planned route stored in modern Electronic Chart Display (ECDIS).

Despite these advancements, human operators have always been central to ship operations, responsible for gathering necessary visual observations within the external navigation environment, assessing operational risks, replanning the voyage if necessary, and making final decisions. However, about a decade ago, a turning point was reached with the resurgence of AI and Machine Learning (ML) methods, enabling unprecedented sensor-data processing and analysis capabilities. This allowed for new functionalities in perception technology that were previously unimaginable, motivating the automotive industry to spearhead the notion of replacing human operators. The maritime industry followed closely, aiming to reduce costs, increase safety, and address the emerging shortage of qualified seafarers. In this pursuit, several high-profile autonomy concepts have been introduced, such as the Yara Birkeland (Yara, 2018) and the Asko barges (Asko, 2022), as seen in Figure 1.

Figure 1. Yara Birkeland (left) and one of the ASKO barges (right). The Yara Birkeland is a battery-powered small container vessel owned by Yara International. Operating between Herøya and Brevik in Norway, it carries fertilizers and chemicals. The ASKO barges are battery-powered barges designed to transport containers across the Oslo fjord, between Horten and Moss in Norway. Both Yara Birkeland and the ASKO barges aim to reduce carbon emissions and road traffic by replacing diesel-powered truck transport.

The initial projects were highly ambitious, aiming for fully uncrewed operation within a few years of their introduction. However, after years of development, many critical challenges remain unsolved, and fully autonomous operations remain elusive. This highlights that replacing the human role is not as straightforward as initially anticipated. The ambition has therefore shifted towards human-machine teaming, where operators remain onboard while being supported by autonomy systems, now serving as advanced Decision-Support (DS) systems. Different autonomy concepts with varying level of manning and automation are illustrated in Figure 2.

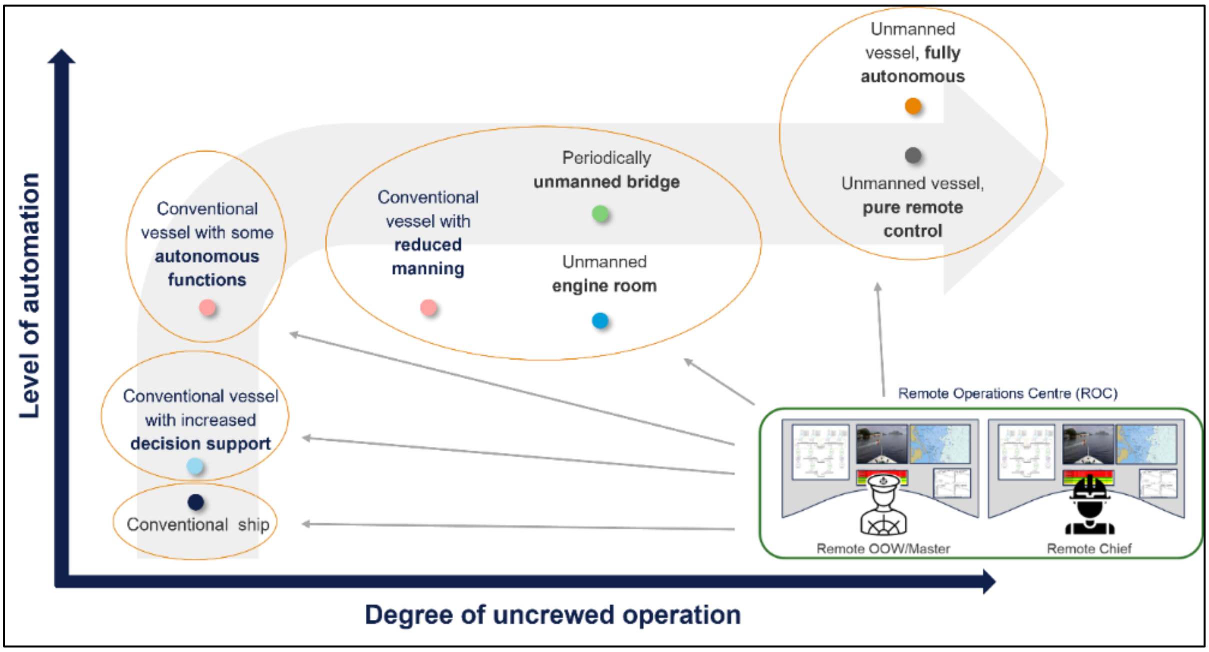

Figure 2. The relationship between manning and level of automation. Fully uncrewed operations can only be realized if a high degree of automation is achieved. Achieving partly automation, only allows for partly or periodical uncrewed operations, simply because there are several functions still relying on the human to perform. The initially high ambitions where to achieve full uncrewed operations, but there are still functions that need human attention, simply because we have not yet proven sufficient automation safety performance.

The transition to fully automated functions faces two fundamental challenges. Firstly, the technology must exhibit sufficient quality, reliability, robustness, and resilience and deliver the necessary functionality to match or surpass the safety performance of human operators, a concept known as the safety equivalence principle (IMO, 2013). Secondly, this performance must be thoroughly demonstrated and documented. Providing evidence to substantiate safety equivalence is a significant challenge for assurance providers (Koopman & Widen, 2023), referred to as the assurance challenge. Addressing this challenge is crucial for the successful deployment of autonomous vehicles across all transportation industries and achieving the initially high ambitions.

2.2. Safety regulations and assurance of MASS

Safety-critical systems must undergo thorough verification to ensure compliance with regulations and standards. This process is crucial for proving the systems' safety performance. Traditionally, in the maritime domain, this verification has been conducted by the Classification Societies, which assess compliance against classification rules and national/international legislation through their roles as Recognized Organisations (ROs). Maritime regulations have traditionally comprised clear prescriptive norms, procedures, and practices to ensure essential safety criteria, complemented by a smaller, selected set of testing activities. These criteria, developed and adapted by generations of marine professionals, reflect centuries of experience in ship design, construction, and operation. They have been sufficient as long as the technological advancements have progressed slowly, allowing the experience-gaining process and rule evolution to keep pace with developments. However, disruptive, software-intensive technologies lacking this historical continuity and collective experience pose an enormous challenge. These technologies fall outside conventional regulations, hindering innovation and have the potential to develop a safety-gap, which kept unsubstantiated, may have severe consequences.

The International Maritime Organization (IMO) has acknowledged this issue and has been working on MASS since 2021, starting with a regulatory scoping exercise under the Maritime Safety Committee (MSC). This led to the preparation of a non-mandatory, goal-based MASS Code (IMO, 2024), expected to be adopted in 2026. The “goal-based” approach sets high-level objectives without prescribing methods, allowing flexibility and innovation. This enables the development of detailed guidance and requirements according to Tier IV of the Goal-Based Standards Framework (IMO, 2019), either by the IMO themselves, or by Classification Societies, see Figure 3.

2.3.Towards detailed guidance and specific performance requirements

The Classification Societies have developed frameworks for Technology Qualification (TQ)[1] to support innovation when existing standards are incomplete (DNV, 2019). The TQ processes allow for alternative designs through risk-based assessments, balancing innovation and safety

[1] In the context of MASS, the Technology Qualification (TQ) process is referred to as System Qualification (SQ) by DNV.

while ensuring that a system or function is safe and fit for purpose in accordance with the equivalence principle.

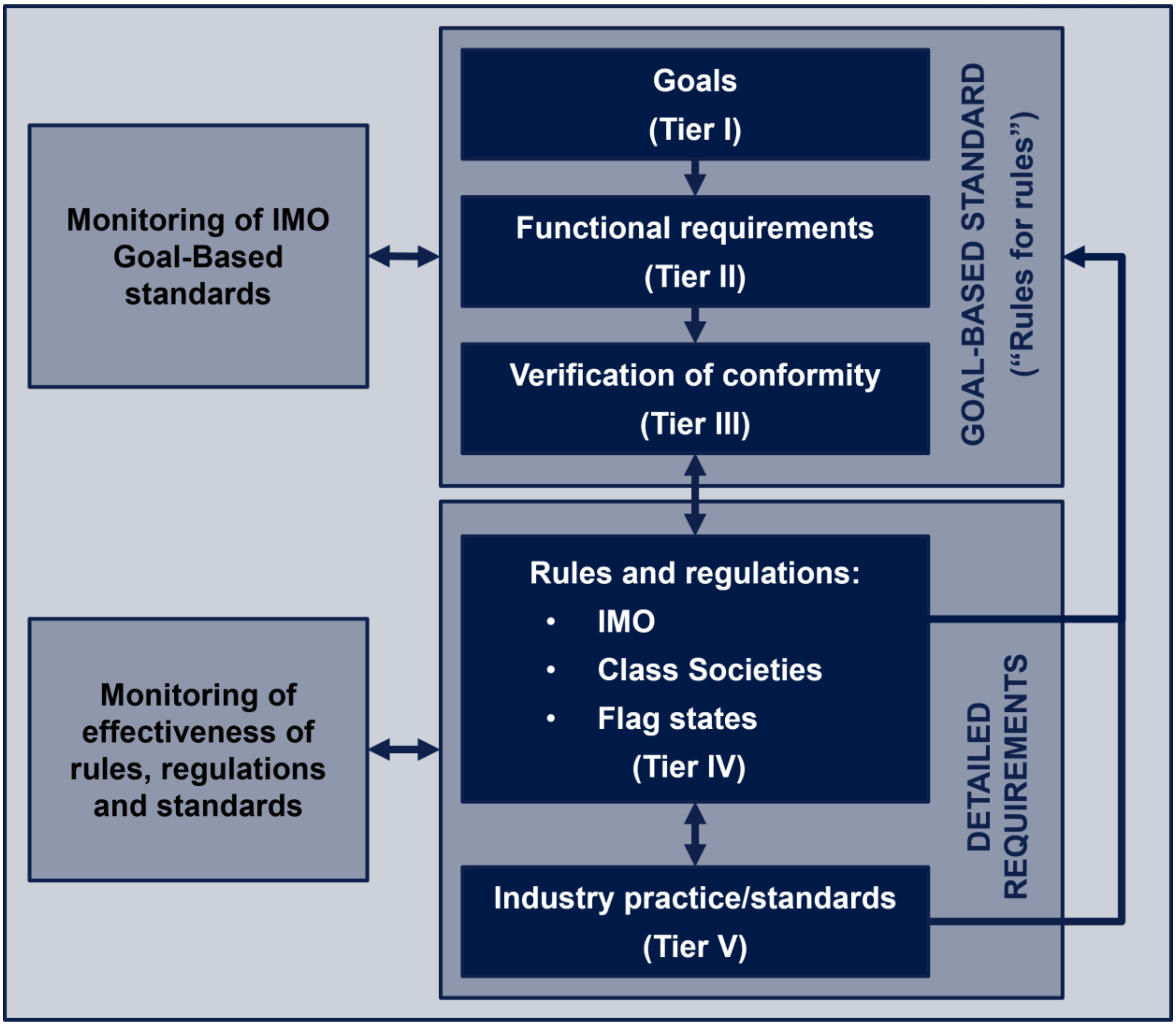

Figure 3. The goal-based standards framework - structured into five tiers: **Goals (Tier I)** are high-level objectives that address the issues of concern and reflect the required level of safety. **Functional Requirements (Tier II)** are criteria to be met to achieve the goals. **Verification of Conformity (Tier III)** involves the instruments necessary for demonstrating and verifying that the associated rules and regulations for ships conform to the goals and functional requirements. The verification process should focus on conformity with the functional requirements. **Rules and Regulations (Tier IV)** are detailed requirements developed by the International Maritime Organization (IMO), national administrations, and/or classification societies. They are applied by national administrations and/or classification societies acting as recognized organizations to meet the goals and functional requirements. Industry **Practice and Standards (Tier V)** may be referenced in the rules and regulations and include standards for shipbuilding, ship operation, maintenance, training, manning, etc.

Figure 4 illustrates the distinction between innovative and mature technology. Emerging technologies, like MASS, are characterized by significant differences in implementation, lack of standardization, and lack of operational data. Typically, safety is ensured through case-by-case evaluation where detailed assurance cases are constructed through the TQ procedure (left side of Figure 4). This approach is flexible but labor-intensive and costly. To address this, Classification Societies have issued technology-specific guidelines to aid vendors and concept owners through the TQ process, moving it slightly toward the maturity side. For MASS, several high-level guidelines have been established by the Classification Societies such as Det Norske Veritas (DNV) (2018), Bureau Veritas (BV) (2019) and American Bureau of Shipping (ABS) (2021).

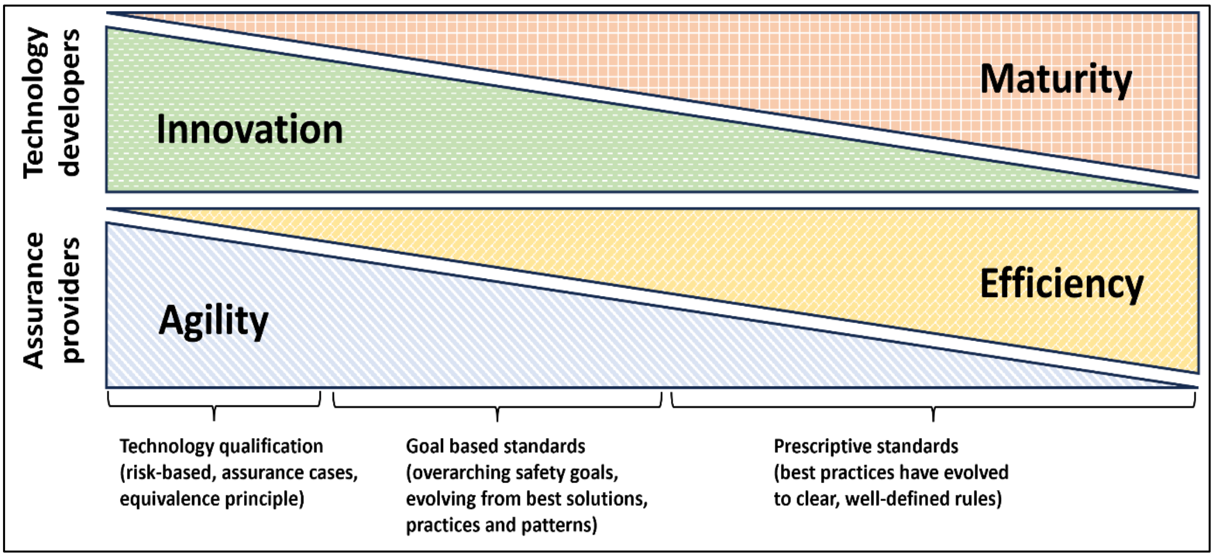

Figure 4. Innovation versus maturity - the need for research diminishes as experience and standardization is achieved. Innovation and uncertainty are replaced by experience and knowledge. The TQ process is found on the left-hand side in the Innovation domain, whereas more traditional and prescriptive rules are found in the right-hand side, in the maturity domain.

While their initial release where on high-level guidance, DNV emphasizes that to properly substantiate equivalence, more detailed functional guidance and requirements are necessary. With this in mind, DNV released an updated version of their guidelines in 2024 (DNV, 2024a), supported by a suite of Autonomous and Remotely Operated Ships (AROS) class notations (DNV, 2024b). These notations focus on functional requirements, providing a framework for how autoremote vessels can achieve safety equivalence. While these guidelines and notations represent a significant milestone and a leap in the right direction, further research and development are needed to create even more detailed system and functional-level guidance and performance criteria for specific system modules. Karolius et al. (2024a) outline several crucial functions and respective parameters necessary for autonomous navigation, arguing that these need to be substantiated with more detailed requirements. One attempt at this was presented in Karolius et al. (2024b), where a probabilistic method for identifying minimum concept-specific detection distances necessary for avoiding collisions was proposed. This represents a first step in developing more specific performance criteria for situational awareness systems for MASS.

2.4. Manage complexity and dependencies through modularization

MASS systems are incredibly complex, integrating a multitude of advanced technologies. These systems rely on a combination of sensors, such as cameras, Automatic Identification System (AIS), Radio Direction and Ranging (RADAR), Light/Laser Direction and Ranging

(LIDAR), etc. to perceive the environment. They use sophisticated algorithms and AI/ML models to interpret this data, make real-time decisions, and navigate safely. Additionally, they must handle a wide range of scenarios, from simple single-ship encounters in good weather, to complex multi-ship encounters in rough and highly dynamic environments, all while ensuring redundancy and fail-safes to prevent accidents. The interplay of hardware and software, along with the need for constant monitoring, makes autonomous technologies highly complex and interconnected.

To develop more detailed performance requirements for these complex and interconnected systems, their behavior needs to be well understood. This is best achieved through a systems-approach (Haugen, 2025), by decomposing the system constituents into more manageable elements, allowing a detailed mapping of their interactions and interdependencies. This includes both interactions and interdependencies between the modules within the system boundaries, but also between the system elements and the environment.

Standardization and modularization have been challenging due to the high variety of autonomy concepts. However, as autonomous systems have matured since their initial introduction, patterns have emerged, enabling some elements to become standardized and modularized for assurance purposes on a more general sense. An attempt to decompose a MASS concept is depicted in Figure 5, showing a system-of-systems hierarchy. The ship, or the autonomy concept, is presented at the top of the hierarchy. The second row represents the various ship functions essential for safe and efficient operation. Although the second row should encompass all principal ship functions, the figure limits the scope of the figure to autonomous navigation due to size constraints. The row immediately below the navigation function shows the various sub-system modules, which together provide all sub-functions of the navigation function. This includes the internal and external Situational Awareness (SA) system as well as the Collision and Grounding Avoidance (CGA) system modules. The bottom row represents components (or units). Each of the sub-modules is built up from a range of different components, such as hardware and software units, comprising various sensors, processing units, power supplies, cabling, etc. For a more detailed description of the individual components and functions of autonomous navigation systems and the functional performance of these see (Karolius 2024a). For more information on assurance of complex systems, see van der Meulen and Myhrvold (2022) and Leveson (2018).

With proper modularization and mapping of module dependencies in place, high-level performance and safety goals can be identified and defined as measurable performance requirements for technical modules or complete systems. These requirements can then be propagated to underlying functions by studying how the performance of the higher-level functions or systems depends on the quality and uncertainty of the output from lower-level functions. This should establish the boundaries of acceptable input/output through the modules of the entire hierarchy, providing detailed and measurable assurance criteria, or assurance contracts (Torben et al., 2023), that can be verified though testing of the complete system, as will be discussed in the next section.

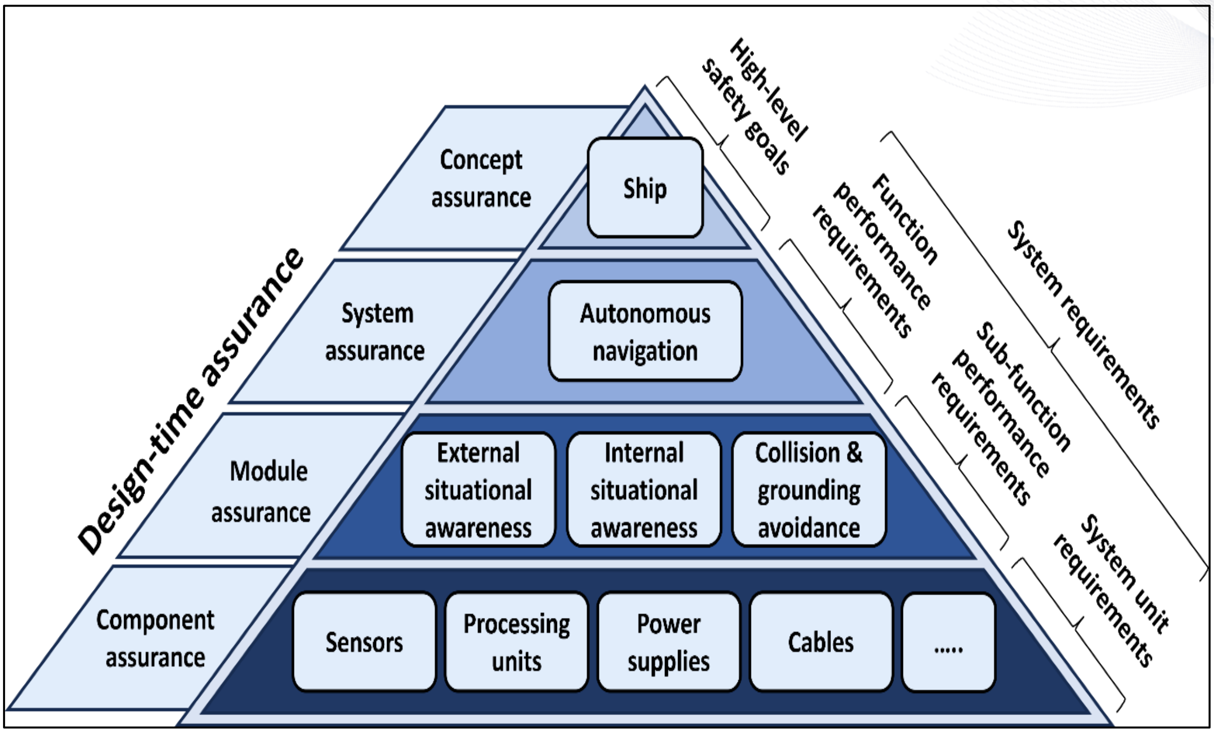

Figure 5. Modularization of MASS concepts, comprising system components (units), system-sub-modules, main-systems, and ship-concept. This specific example focuses on the autonomous navigation system (ANS), comprising two sub-system-modules: external/internal Situational Awareness (SA) and Collision & Grounding Avoidance (CGA).

2.5. Chasing the tail of events using simulation-based verification

Verifying safety performance of autonomous systems is a highly challenging task due to the systems complexity, reliance on software and AI, and operation in dynamic and uncertain environment. The operational boundaries of these systems, often referred to as the Operational Design Domain (ODD) (AVSC, 2020), encompass a nearly infinite number of variables in a high-dimensional space that may affect performance. Real-life testing of the complete ODD variable-space and respective test-scenarios is not feasible due to the high cost, required time, and associated risks. This issue is particularly pronounced in the maritime industry, where designs and technical solutions are often tailor-made to individual ship concepts, or in the best case, a few sister vessels, rather than mass-produced as in the automotive industry.

The solution involves two key components: system modularization and the identification of performance (assurance) criteria, as discussed in the previous section, and the use of simulators for testing with sufficient coverage (Huang et al., 2016; Koren & Kochenderfer, 2019; Pedersen et al., 2020). Figure 6 illustrates the goal of testing, which is to identify and test a sufficiently large number of scenarios to ensure that the likelihood of remaining dangerous corner cases is at an acceptable level, i.e. acceptable residual risk. This challenge must be addressed in the overall assurance process and by the testing strategy.

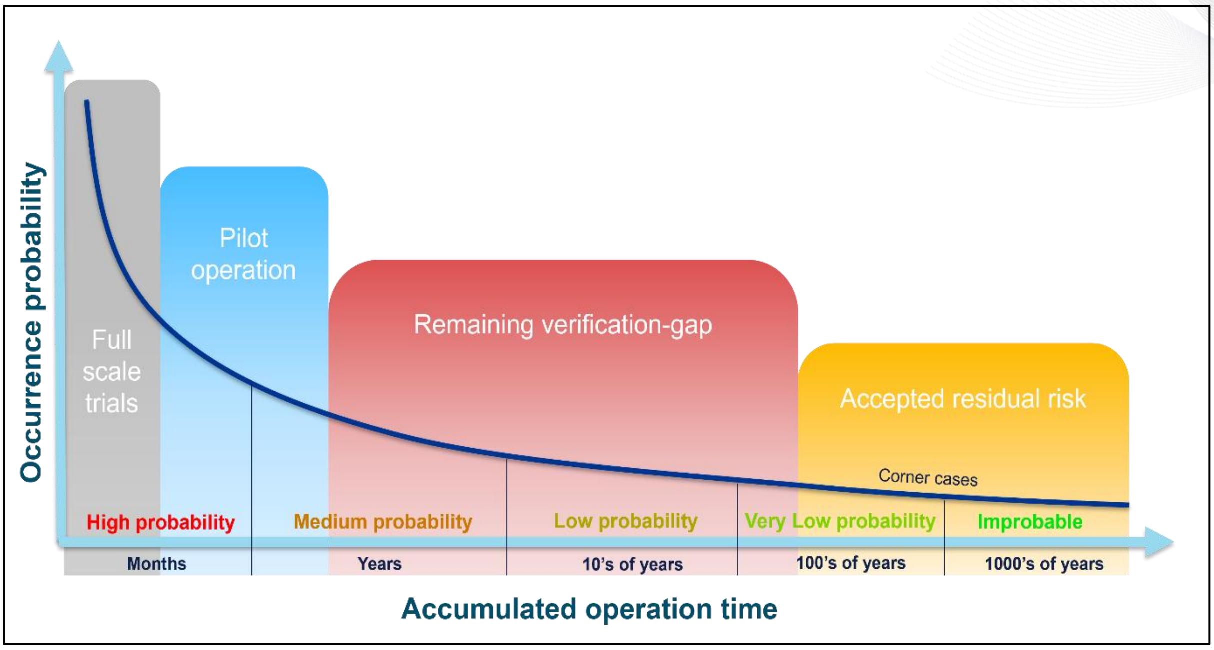

Figure 6. Chasing the tail of events to reach acceptable residual risk: Complex software and AI intensive systems have an infinite parameter space which makes getting sufficient test coverage a major challenge. The goal of testing is to cover enough scenarios and situations to ensure that the remaining (residual) risk is acceptable.

Simulators create synthetic representations of the navigation environment and ship systems, interfacing with actual hardware or software through Hardware-in-the-Loop (HIL) and Software-in-the-Loop (SIL) testing. The term simulation covers a broad range of tools and models used for various testing purposes, which can significantly differ in their fidelity levels—the degree to which they replicate the real world. High-fidelity simulators offer a detailed and realistic representation of the world's features, often requiring more computational resources. Conversely, low-fidelity simulators provide a less accurate representation but are computationally more efficient. The concept of varying fidelity levels is depicted in Figure 7.

Figure 7. Example screenshots of simulator-based testing of ANS systems. High fidelity (3D game engine based) simulator (AI Livesim, 2018) for testing of external situational awareness system (left), and a simplified (2D) low fidelity simulator (Karolius et al., 2024b) for high volume testing of collision and grounding avoidance systems (right).

This variability allows for customization, enabling adjustments in different aspects of the simulator to achieve the necessary accuracy for specific tests. For example, while simulators based on the Unreal or Unity game-engines (Unreal, 1998; Unity, 2005) are renowned for their detailed visual environments, they may not necessarily provide an accurate representation of the physical behaviors of objects within those environments. In scenarios where testing an AI-based computer-vision detection and classification algorithm, a high-fidelity visual environment is crucial to supply the AI with realistic imagery. On the other hand, for evaluating a CGA system in isolation, the visual and spatial details are less significant than the precise depiction of objects' behavior and interaction with surrounding target vessels and the physical environment. Ultimately, the nature of the tests determines the required combination of fidelity levels within the simulation environment, ranging from unit, module, system, and complete end-to-end testing of the entire MASS concept.

Even with advanced simulators, the ODD test-space is immense and requires processes for smart testing for proper resource-allocation and prioritization to strike the right balance between accuracy and coverage. Torben et al., (2022) outlines a method for automatic (smart) testing of CGA systems using gaussian processes and temporal Logic motivated by the need for increased test coverage. Karolius et al. (2024a) also discuss, on a more general level, the need for resource allocation between the fidelity-levels for optimal use of available resources. It is argued that it is practical to start in the low-fidelity domain to produce broad evidence across the entire test-space. Although less accurate, this approach yields evidence on a larger scale, aiding in the identification of areas within the test-space that require further investigation. Subsequently, these regions can be subjected to high-fidelity simulations for a more detailed assessment. Resource allocation allows more accurate but computationally expensive resources to be allocated to where they matter the most—in the regions of the test-space that contains high-risk, and high-uncertainty test scenarios. Similarly, in the high-fidelity domain, simulations can be used to narrow down the regions in the test-space and related test scenarios that necessitate real-life testing.

Another important aspect to cover in testing is emerging properties from the integration of multiple complex software systems and other onboard systems. Uncovering these types of problems requires closed-loop simulations with the integration of all relevant components, in addition to onboard system integration testing. The resource allocation process is depicted in Figure 8, which also highlights the importance of incorporating evidence from selected real-life tests to validate the simulators' accuracy and representation of the real world. Achieving an optimal balance in resource allocation is crucial for conducting effective tests and acquiring precise and sufficient evidence to assess the system's overall safety level throughout the assurance process. However, identifying the ideal combination of detail and adequate test scope remains an unresolved challenge, necessitating further research.

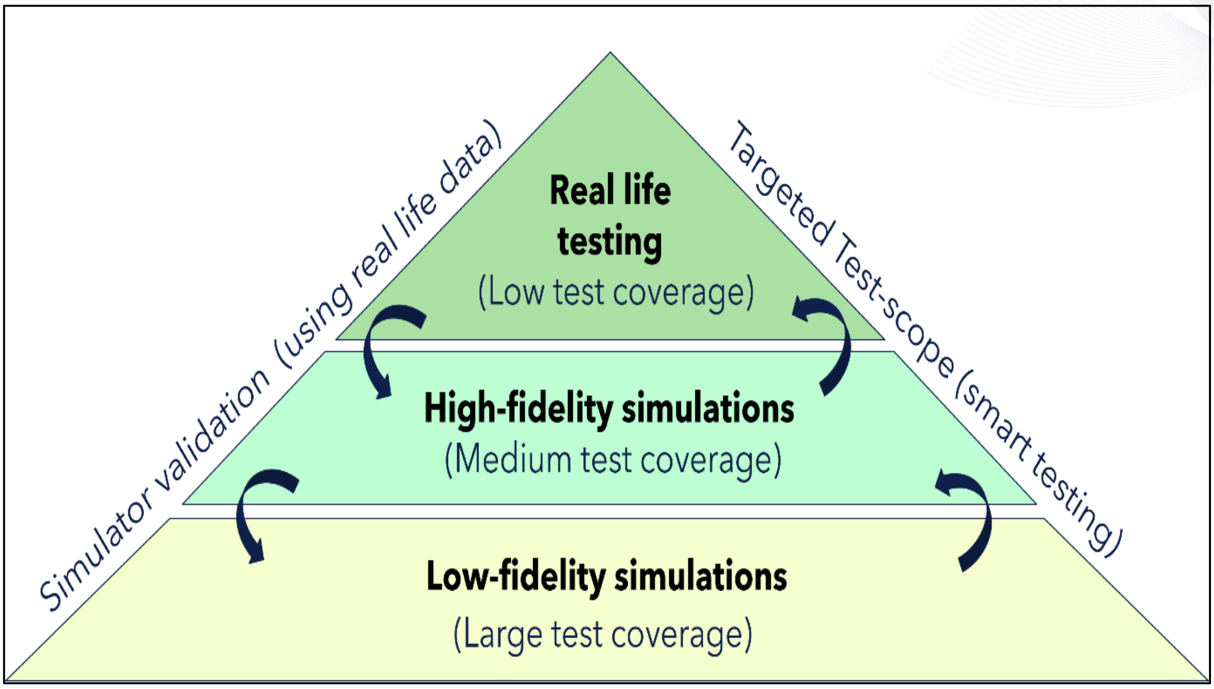

Figure 8. Resource allocation for synthetic simulations: Large-scale simulations in the low-fidelity domain can be used to traverse larger areas of the ODD test-space, aiding in the identification of areas within the test-space that require further, more detailed investigation using higher fidelity-levels. Likewise, high-fidelity simulation results can identify regions in the test-space that needs to be tested in real-life. Test data from the actual asset is also required to verify the simulation models, ensuring their representation of the real-world is satisfactory.

3. Discussions and concluding remarks

Building on previous studies (Karolius et al., 2024a; Løvoll et al., 2024), this comprehensive overview discusses the advancements and challenges in the field of Maritime Autonomous Surface Ships (MASS) and related technologies. Significant progress has been made due to digitalization, AI, and sensor technologies, laying the groundwork for the autonomous revolution. However, the rapid pace of these developments may lead to a safety gap, as existing regulatory instruments and assurance methodologies are not keeping up with emerging technologies and concepts.

The initial ambitions for uncrewed operations were high, but they have not been fully realized. Completely replacing human operators with autonomous systems is more challenging than initially anticipated. This realization has shifted the focus towards decision support systems, where human operators are still necessary for supervision. Underestimating the importance of proper assurance and assessment of human-machine interfaces (van de Merwe, 2024), as well as human operator training, could be detrimental.

The challenges lie in developing technology that possesses quality, robustness, reliability, and functionality equivalent to human operators. It is crucial to verify and prove this equivalence through well-defined assurance processes and tools. Currently, there are no international instruments regulating MASS technologies directly. The safety-equivalence principle is supported by Class Societies' guidelines, which aid technology providers through their Technology Qualification (TQ) processes. These guidelines, however, only include high-level processes and ship functions and lack detailed performance requirements.

Providing evidence of safety equivalence is an immensely challenging task that necessitates the use of simulator tools for traversing the Operational Design Domain (ODD) test space. Even with simulators, the test space is immense and requires smart testing processes and proper resource allocation and prioritization. Low-fidelity evaluations allow for broader insights across the entire test space. While less accurate, they provide large-scale evidence, pinpointing parameter space regions and specific test scenarios that may require high-fidelity simulations for a more thorough examination. This strategic distribution of resources ensures that the more precise, but resource-intensive tools are utilized where they make the most impact in high-risk, high-uncertainty areas of the test space. Similarly, high-fidelity simulations can reveal test scenarios that warrant real-life testing.

Achieving balance in resource allocation is crucial for conducting effective tests and acquiring precise and sufficient evidence to assess the system's overall safety level throughout the assurance process. The detailed quantitative requirements and methods to assess fulfilment are, however, an unresolved challenge, necessitating further research. Assuring the safety of MASS and their systems is a critical challenge that must be solved to unlock their full commercial potential. This highlights the vital role of skilled third-party assurance providers. In a domain characterized by ever-evolving technologies and a vast array of disparate technology vendors and complex systems attempting to integrate on highly unstandardized assets, Classification Societies are becoming increasingly important.

To bridge the emerging safety gap when increasing the level of automation and replacing human operators, the following key research questions and challenges must be addressed:

- Develop technology-specific guidelines and detailed performance requirements to substantiate safety equivalence.
- Link performance criteria to overarching safety goals.
- Develop methodologies and simulators to efficiently test the performance criteria.
- Identify the ideal combination of detail and adequate test-scope in simulation testing methodologies, determining how much evidence is sufficient.
- Develop standard interfaces and data exchange formats to facilitate third-party testing of critical components and complete systems.
- Manage the complexity and dependencies by developing or adopting appropriate methods for analyzing and modularizing the system into manageable elements.
- Address emerging properties from system integration by identifying and managing the emerging properties that arise from the integration of multiple complex software systems and other onboard systems.
- Ensure proper human-machine interaction by assessing and assuring the relevance and effectiveness of human-machine interfaces, as well as the training of human operators who will supervise or interact with autonomous systems.

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3. Proactive Maritime Traffic Management Utilizing Dynamic Accident Networks (DANs)

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Abstract: Maritime safety in high-traffic areas, including narrow waterways, Traffic Separation Schemes (TSS), and port approaches, is a long-standing concern requiring advanced tools to address multifactorial risks and support operational decision making. Despite advancements in maritime technology and navigation systems, operational conditions, human and organizational factors remain critical in accident causation. Even in the era of autonomy and digitalization it is relevant, where manned, partially unmanned, and unmanned ships will coexist across different degrees of autonomy (D1-D4). Traditional accident analysis models often lack the capacity to dynamically incorporate real-time and complex operational variables. The maritime industry mostly relies on occurrence and casualty investigation reports to learn from the past and prevent in the future. To move towards proactivity, this study introduces a dynamic accident prediction model that integrates the Human Factors Analysis and Classification System (HFACS) with Bayesian Networks to assess and mitigate risks effectively in real-time and support operational decision making. Utilizing marine casualty data and incorporating expert insights, the model provides a probabilistic framework to support proactive decision-making for vessel traffic service (VTS) operators, ship masters and other maritime stakeholders. The model's application aims to enhance navigational safety and operational efficiency, by offering insights for decision making that will ultimately reduce accidents and enhance sustainable maritime operations.

Keywords: Multi-criteria decision making; Bayesian belief networks; Human and organizational factors; Maritime traffic management; Marine casualties and incidents

1. Introduction

High-traffic marine areas, serving as arteries of global trade, playing a crucial role in the global economy (Meza et al., 2022; Yıldız et al., 2024). Some examples of these areas, including but not limited to narrow waterways like Turkish Straits System, Singapore Strait, English Channel, Malacca Strait, Suez Canal, and the Panama Canal, facilitate the movement of a significant portion of the world's trade volume. According to the United Nations Conference on Trade and Development (UNCTAD), over four fifth by volume are carried by sea and are handled by ports worldwide, emphasizing the importance of sea routes (UNCTAD, 2024). High traffic in narrow waterways, combined with complex environmental conditions, operational conditions and human factors, poses substantial challenges to navigational safety (Gao et al., 2024; Yildiz et al., 2022). Studies indicate that high traffic density significantly increases the risk of marine casualties and incidents (Pelot and Plummer, 2009; Tonoğlu et al., 2022). Furthermore, environmental factors such as heavy seas, fog, ice, and strong currents complicate navigation and risk management. Human errors, often stemming from fatigue, poor decision-making, or inadequate training, continue to be a leading cause of maritime incidents (Dominguez-Péry et al., 2021; Maternová et al., 2023; Oraith et al., 2021).

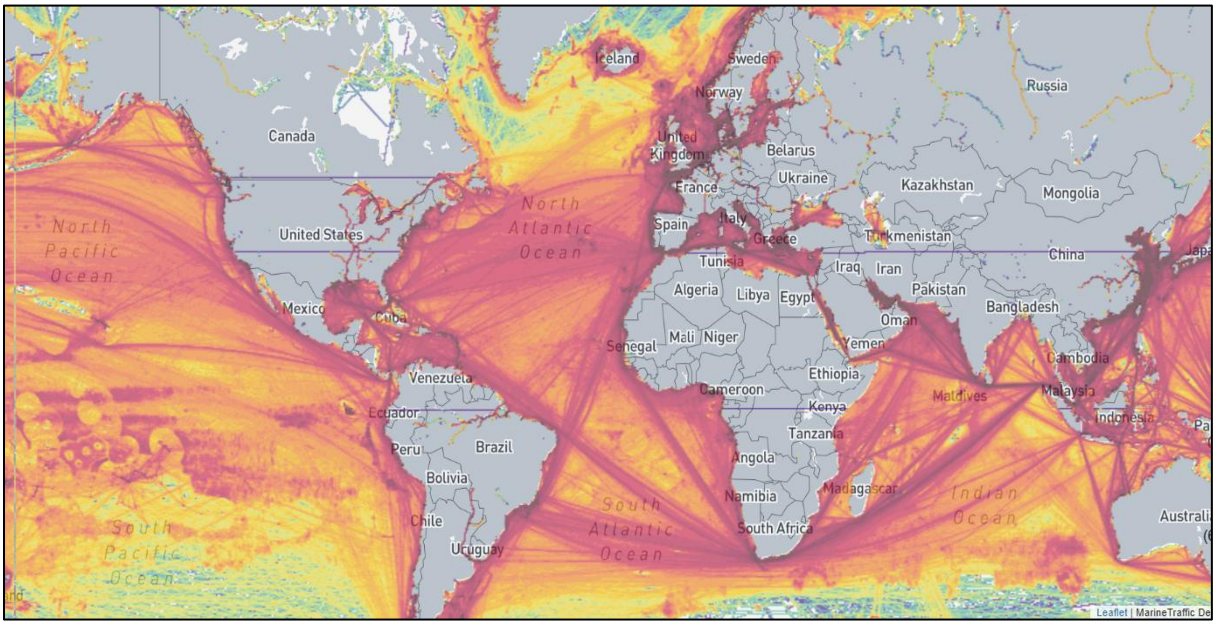

Figure 1. Vessel traffic density map (AIS Marine Traffic, 2025).

Additionally, the evolution of maritime technology has started introducing unmanned vessels, which coexist with manned ships across various stages of autonomy (Degree 1) to fully autonomous operations (Degree 4) (Kim et al., 2022; Nakashima et al., 2024). This integration presents both opportunities and challenges for collision avoidance and traffic management in congested waters (Felski and Zwolak, 2020; Levander, 2017). Marine casualties and incidents are rarely the result of a single cause and usually occur as a result of complex interactions between environmental factors, operational conditions, human error, equipment failures, and navigational complexities (Dominguez-Péry et al., 2021; Kasyk et al., 2023). Figure 2 presents an illustration of occurrence of marine casualties using Reason's Swiss Cheese Model (Reason et al., 2006).

Major incidents in high-traffic zones not only disrupt global supply chains but also have severe economic and ecological impacts. For example, the collision in the Strait of Malacca in 2017 resulted in significant oil spills, disrupting traffic and causing extensive environmental damage (ITOPF, 2018). Similarly, the blockage of the Suez Canal by the Ever Given in 2021 underscored the vulnerability of these chokepoints, halting $9 billion worth of daily maritime traffic and impacting global markets (Allianz, 2021). Thus, enhancing navigational safety in these critical areas is imperative to sustain the efficiency of global trade routes and mitigate the potential for catastrophic incidents.

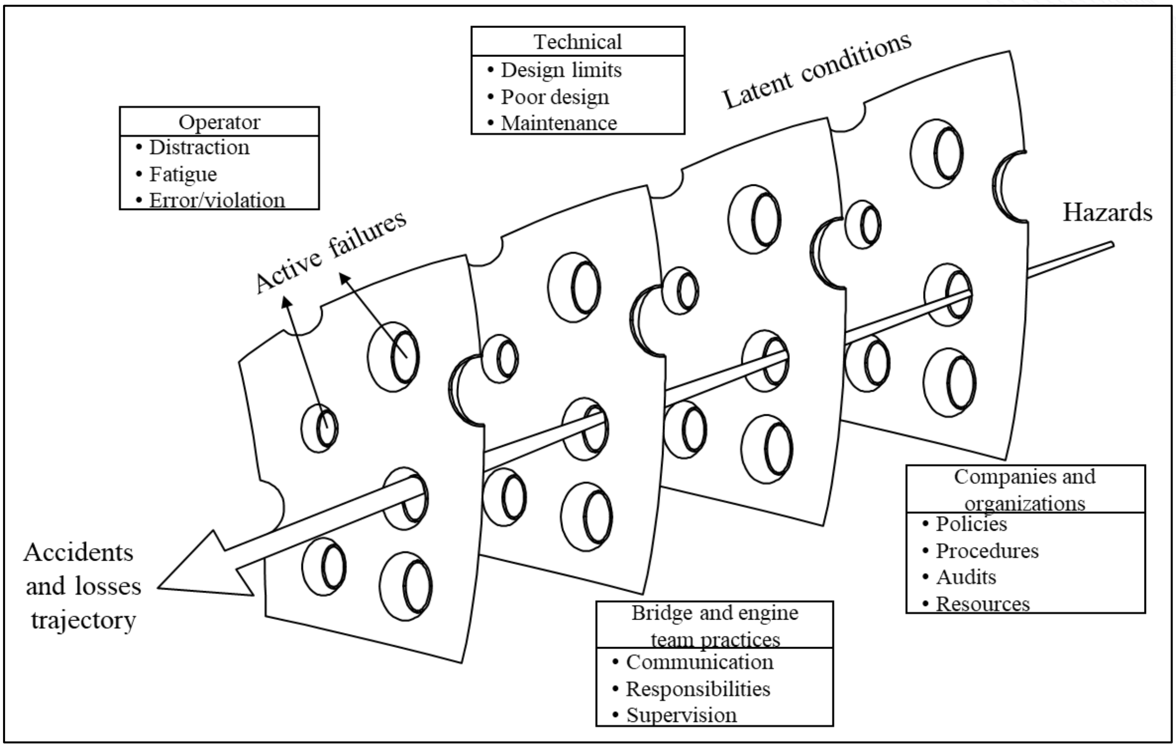

Figure 2. Marine casualties' occurrence pattern along with Swiss Cheese Model

2. The need for a decision support system for maritime traffic management

The necessity for an advanced traffic management system supported with an accurate decision support system in high-density maritime areas is driven by the escalating complexity of navigational environments. As maritime traffic continues to grow, especially in key chokepoints, the task of managing such areas becomes increasingly intricate. UNCTAD predicts that seaborne trade volumes will continue to rise, projecting an annual growth rate of 2.1% from 2023 to 2028 (UNCTAD, 2024). This surge underscores the critical need for robust systems capable of handling heightened traffic densities efficiently. Additionally, the integration of autonomous vessels into existing fleets of manned ships introduces new dynamics into maritime traffic management. Autonomous vessels operate with varying levels of independence from human operators, from semi-autonomous systems that require human oversight to fully autonomous systems that operate independently. This mixture poses unique challenges for collision avoidance and traffic coordination (Felski and Zwolak, 2020; Kim et al., 2022).

Traditional accident analysis and prediction models, which often rely on historical data and static parameters, struggle to accommodate the dynamic interactions and continuous changes in autonomous and manned vessel operations. These models frequently fail to capture the nuances of mixed environments, which are characterized by varying degrees of autonomy and human involvement (Kaber, 2018; Lyons et al., 2021). Consequently, there is a marked need for updated models that can dynamically adapt to the evolving conditions and provide accurate risk assessments in real-time. Traditional, reactive approaches to maritime safety are insufficient and that has been noticed long back since 1960s and shifted the focus on, proactive measures, predictive risk assessment, real-time traffic management with decision support systems for operators (Luo and Shin, 2019).

To address these complexities, there is a need for real-time decision support systems that can assist Vessel Traffic Services (VTS) Operators, ship masters, bridge team members and other maritime stakeholders. Such systems are designed to provide immediate, data-driven insights into potential navigational risks and optimize traffic flows within congested maritime zones. By leveraging advanced algorithms and real-time data, these decision support systems can enhance situational awareness and decision-making processes, thereby improving safety and efficiency in maritime operations (Baldauf et al., 2020). Therefore, this study is focused on addressing the need for improved safety and efficiency in high-traffic maritime areas by achieving the following objectives.

i. To develop a hybrid model for predicting marine accidents in high-traffic maritime areas by recognizing the limitations of current predictive models, the study aims to develop a hybrid model that combines quantitative and qualitative data analysis techniques.
ii. To integrate the Human Factors Analysis and Classification System (HFACS) with Bayesian Networks for dynamic and real-time risk assessment: HFACS provides a framework for identifying and analyzing human error aspects of accidents, which are a significant cause of maritime incidents. Integrating HFACS with Bayesian Networks, which offer probabilistic insights based on causal relationships, this study aims to facilitate dynamic and real-time risk assessment.
iii. To propose areas of improvement for reducing accident probabilities and improving decision-making by analyzing the data generated through the hybrid predictive model and the integrated HFACS-Bayesian framework.

4. Overview of accident analysis models

Accident analysis models are essential tools in identifying the root causes of incidents and developing effective prevention strategies (Wong and Pawlicki, 2025). Traditional models in marine casualty analysis often focus on either human error or technical failures. These models, while providing valuable insights into specific sides of accident causation, typically do not address the complex interplay between various elements such as human factors, organizational processes, and environmental conditions. Studies have shown that focusing solely on one aspect can lead to an incomplete understanding of accident causation and potentially overlook critical preventive measures (Salehi et al., 2021; Zarei et al., 2022).

In response to the limitations of traditional models, hybrid models have emerged as a promising alternative. Hybrid models integrate multiple qualitative and analytical methods to provide a more comprehensive understanding of accident causation (Tonoğlu et al., 2022; Yildiz et al., 2021). These models leverage the strengths of individual approaches to address the multifaceted nature of marine casualties and incidents, enhancing both the depth and breadth of analysis. For instance, hybrid models can simultaneously evaluate human factors, technical conditions, and environmental influences, providing a holistic view of the risk landscape.

Among the tools used in these hybrid models, the Human Factors Analysis and Classification System (HFACS) and Bayesian Networks are noteworthy and frequently used in literature. HFACS is a widely recognized framework for identifying and classifying human errors involved in accidents. Developed initially for aviation and later adapted for maritime contexts, HFACS facilitates a structured analysis of human errors from multiple levels, including organizational influences, unsafe supervision, and conditions of operators' actions (Ergai et al., 2016; Li and Harris, 2006; Salmon et al., 2012; Theophilus et al., 2017; Uğurlu et al., 2018).

Bayesian Networks, on the other hand, offer a probabilistic approach to modelling the causal relationships between various risk factors. These networks are capable of incorporating uncertainties in the data and can update their predictions as new information becomes available, making them highly effective for dynamic and complex environments like maritime traffic (Yang et al., 2008; Yeo et al., 2016; Yıldız et al., 2024). The application of Bayesian Networks in maritime safety allows for real-time risk assessment and decision-making support, adapting to changing conditions and operational contexts. Bayesian Networks based DANs represent occurrences as a network of interconnected operational conditions, human and organizational factors, capable of incorporation real-time data to dynamically update risk assessments, and to simultaneously analyze wide range of factors, vessel characteristics, weather conditions, traffic patterns, and human factors.

5. Methodology

5.1. Data collection

The foundation of this study is based on a data collection strategy that involved gathering historical accident data from databases such as the Global Integrated Shipping Information System (GISIS) and IMO member States' national databases such as the Maritime Administrations transport safety databases or transportation safety investigation center/board of the member States. Initially, records of 366 marine casualties and incidents occurred between 2010-2024 were collected from these sources (EMSA, 2024; GISIS, 2024). After data screening and cleaning, 10 duplicate records were deleted, and 76 accident reports could not be retrieved. Ultimately, 280 marine casualty reports, focusing on navigation-related incidents such as strait passage, strait approach, port approach, and coastal traffic zone navigation, have been compiled as the main dataset for this study.

Expert judgements were another input as a dataset used in construction and validation of the accident network. It involved consultation with 10 maritime safety experts, including accident investigators (3 experts), ship masters (2 experts), chief engineers (2 experts) and scientists involved in marine casualty investigations (3 experts) to gain insights that are not readily available in public databases such as accident occurrence patterns as dynamic accident (Bayesian) networks. These experts provided nuanced interpretations of processed casualty data, highlighted and validated lesser-known risk factors or operational conditions.

5.2. Model development

The model development phase began with the establishment of a framework based on the Human Factors Analysis and Classification System (HFACS) for each of the 280 marine casualties. In the utilized HFACS-PV human factors and operational conditions were categorized into four levels: Organizational Influences, Unsafe Supervision, Preconditions for Unsafe Acts, Unsafe Acts and Operational Conditions. Each level addresses different aspects of human factors contributing to marine casualties and incidents, offering a structured approach to understanding the interactions between human errors and other accident causation factors. In the marine casualties and incidents context organizational influences generally refer to the overarching policies, culture, and management practices that shape the operational environment of ships, potentially leading to safety oversights. Unsafe supervision usually refers to failures in leadership and oversight that allow or fail to correct risky practices before they lead to accidents. Preconditions for unsafe acts pave the way for unsafe acts of the individuals, including technical, and human conditions, such as fatigue or inadequate training. Unsafe acts are errors or violations committed by individuals directly involved in operations and usually complete the accident occurrence pattern, which are often seen or found as the immediate causes of incidents. Operational conditions encompass the specific environmental, technical, and situational contexts in which maritime operations occur, such as adverse weather or high traffic density, which can significantly influence the likelihood and severity of accidents (Shappell and Wiegmann, 2000; Uğurlu et al., 2018; Uğurlu et al., 2020; Yildiz et al., 2021).

Integration with Bayesian Networks was the next step in the model development. Bayesian Networks were utilized to estimate prior probabilities of various accident scenarios, considering the interdependencies among HFACS levels (Uğurlu et al., 2020; Yıldız et al., 2024). This probabilistic model is capable to adapt to new information continuously, thereby providing real-time risk assessments.

Constructing the dynamic network model involves four steps *i. Identification of variables*: Key risk factors are identified based on HFACS levels and additional data from historical accident reports and expert input. *ii. Structural modelling:* A network structure is developed to represent causal relationships between identified risk factors. *iii. Parameterization:* Conditional probability tables are created for each node, based on historical data and expert judgments. *iv. Validation and calibration:* The model is iteratively adjusted and calibrated to align with known accident outcomes and expert assessments.

Expert validation was an integral part of the methodology. This phase involved a 3-hour focus group exercise with 10 experts participated in the study as specified above. Essentially the proposed DAN presented to the experts and they reviewed the model's outcomes, provided feedback on its practical relevance, and contributed to refining the probabilistic relationships and assumptions within the model (Uğurlu et al., 2020; Yıldız et al., 2024). This collaborative approach ensures that the model not only reflects theoretical accuracy but also aligns with practical realities in maritime operations. Figure 3 outlines the step-by-step methodology followed in this study.

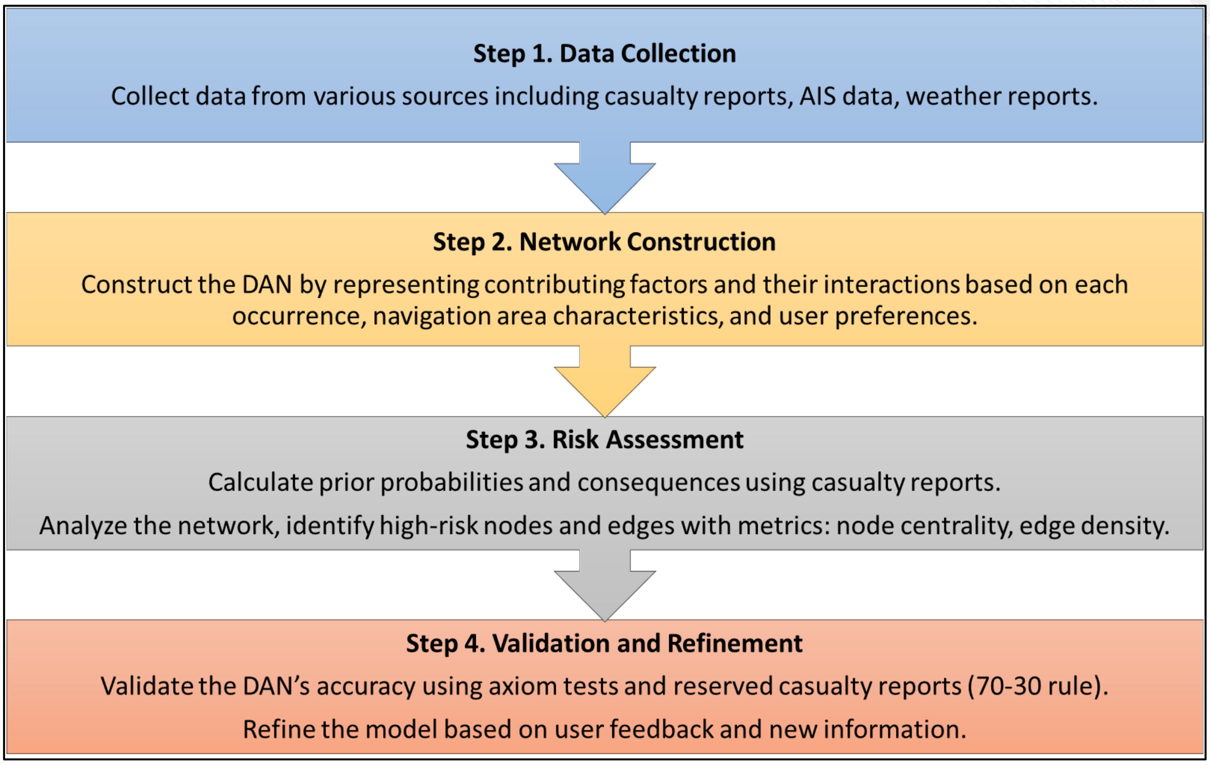

Figure 3. Step-by-step methodology followed in the study

6. Proposed Dynamic Accident Network (DAN)

In high-traffic maritime areas managing navigation and ensuring safety are particularly challenging. These areas, which experience dense maritime traffic and contain numerous navigational constraints, are prone to accidents influenced by a complex interplay of various causal factors (Tonoğlu et al., 2022; Yildiz et al., 2022; Yıldız et al., 2024). Understanding the causes and their interactions is essential for risk assessment and accident prevention.

From the DAN model developed in this study, several key nodes represent causes and causal factors that directly contribute to marine casualties and incidents more frequently than others. These factors are grouped under human, organizational, environmental, and technical domains as reflected with different colors in the Figure 4.

- Organizational Influences; *Safety culture:* A strong safety culture in maritime organizations supports proactive safety and compliance behaviors. *Company's manning strategy and crew assignment:* Adequate staffing and proper assignment of crew roles are crucial to ensure all operations are performed by competent personnel. *Procedures and rules:* Established protocols help standardize operations and reduce the chance of accidents.
- Technical and Operational Supervisory Factors (Unsafe Supervision); *Equipment and facility resources:* The reliability of a ship's equipment and the maintenance status directly impact the risk of mechanical failures. *Voyage and operation planning:* Comprehensive planning is vital to foresee and mitigate potential risks associated with the voyage.

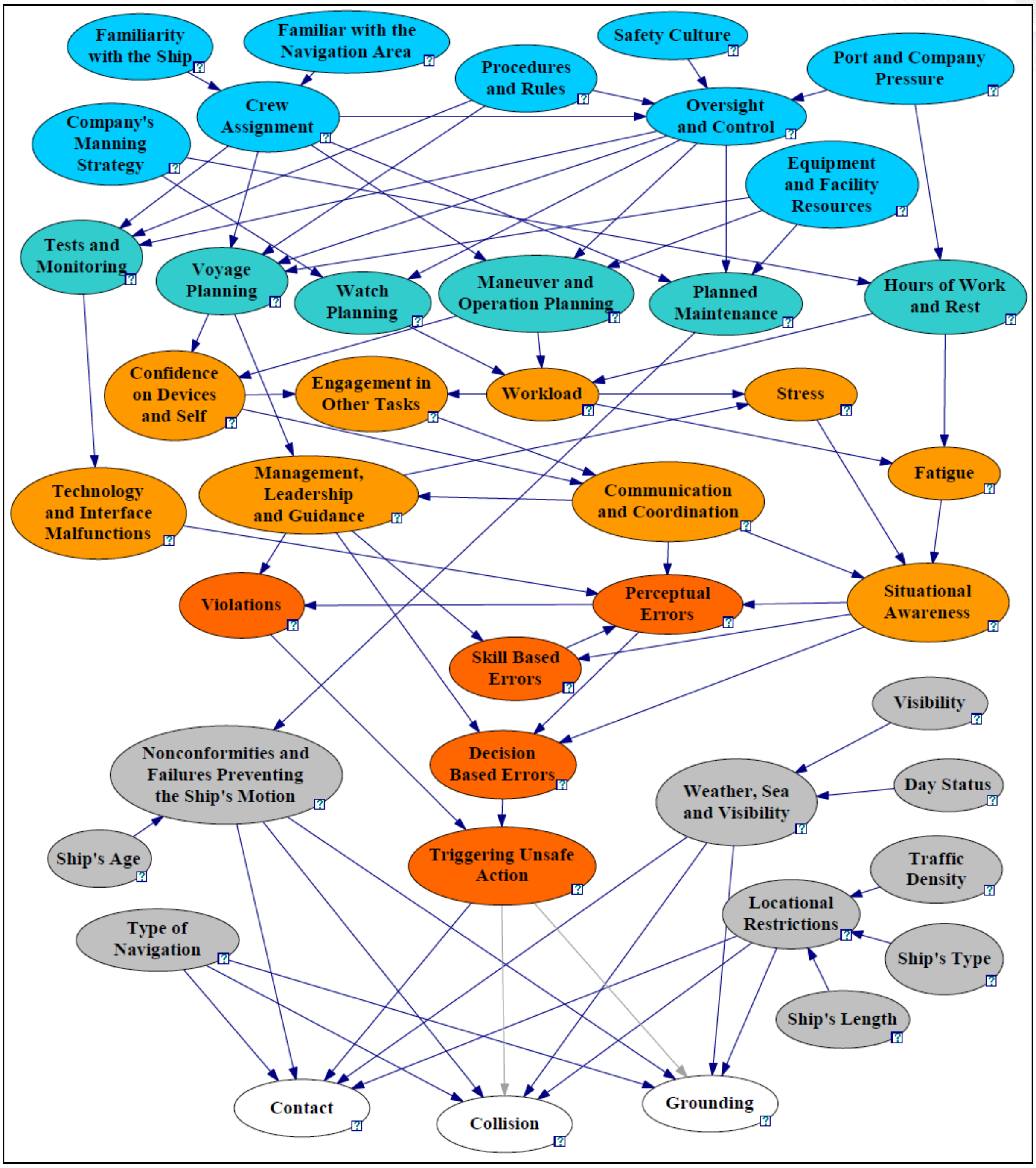

Figure 4. Overview of the proposed Dynamic Accident Network

- Human Factors; *Familiarity with the ship and navigation area:* Proficiency and experience of the crew with the specific vessel and the local waterways significantly affect navigational safety. *Hours of work and rest:* Fatigue related to non-compliance with work and rest schedules can lead to decreased alertness and increased likelihood of errors. *Confidence on devices and self:* Over-reliance or underestimation of navigational aids and personal judgment can lead to critical misjudgments. *Skill-based, perceptual, and decision-based errors:* These errors include misinterpretation of navigational data, poor decision-making under pressure, and execution failures.

- Operational and Environmental Conditions; *Weather, sea, and visibility conditions:* Adverse weather and poor visibility increase the complexity of navigation and risk of accidents. *Traffic density and type of navigation:* High traffic density and the mix of different vessel types (e.g., cargo, tanker, passenger) elevate the potential for conflicts and collisions.

Using the developed hybrid model, this study analyses how these causal factors influence the probabilities of different types of marine casualties and incidents under varying operational conditions in the strait. Factors such as vessel speed, weather conditions, and crew fatigue are modelled to estimate the likelihood of incidents such as collisions, groundings, contact accidents, and sinkings.

The model is capable to predict:

- Collision probability: Heightens in scenarios with high traffic density, especially when compounded by poor visibility or crew fatigue.
- Grounding probability: Increases in areas with geographical constraints, particularly when navigational planning is inadequate.
- Contact probability: Rises in close-quarter situations are often influenced by miscommunications or navigational errors.

The effectiveness of preventive measures such as pilotage and timing adjustments for transits is evaluated, showing considerable reduction in accident probabilities. The case study underscores the importance of a comprehensive approach to understanding and managing the multifaceted risks in high-traffic maritime areas. By addressing the interrelated causes and factors, the hybrid model aids in enhancing maritime safety in high traffic areas.

7. Results and discussion

The application of the DAN model to high-traffic maritime areas has provided insights into the risk factors and their implications for maritime safety. The model highlights several high-risk factors crucial in these environments (Figure 5).

Organizational Influences: Adequate manning and safety culture are shown to be vital, with 91% of scenarios featuring qualified crew assignments and 99% reflecting an optimum safety culture. These factors are directly linked to lower incident rates in the model predictions.

Technical and Operational Supervisory Factors (Unsafe Supervision): Equipment and procedural adequacy are also highlighted, with inadequacies in these areas present in 12% and 14% of scenarios, respectively. These shortcomings can lead to critical operational failures and errors.

Human Factors: Fatigue and stress are prevalent issues, with the model indicating that 44% of scenarios involve fatigue, and 24% involve high stress levels among the crew. These factors substantially increase the likelihood of human errors in decision-making and operation.

Operational and Environmental Conditions: Visibility and traffic density are significant environmental factors affecting risk. The model indicates that poor visibility conditions occur in 1% of scenarios, and high traffic density is present in 30% of scenarios, both of which increase accident probabilities.

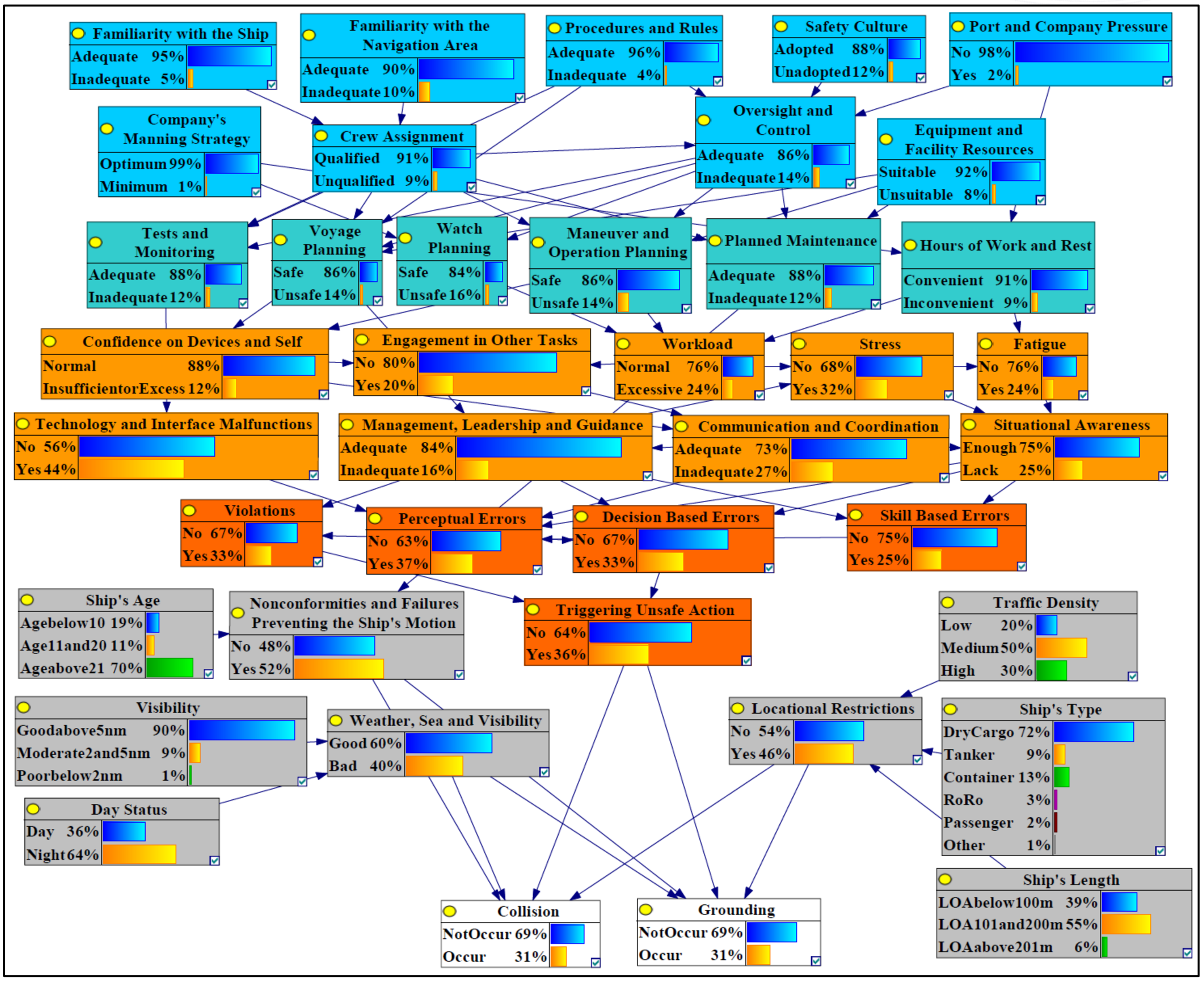

Figure 5. Proposed DAN with probabilities

The DAN model's ability to dynamically predict accidents under varying operational conditions provides actionable insights into real-time decision making. By quantifying the probabilities of different accident types, such as collisions and groundings, which each occur in 31% of scenarios under certain conditions, the model aims to allow VTS operators, ship masters and bridge team members to adjust their strategies based on current risk assessments.

The findings from the DAN model align with existing literature that emphasize the critical role of human factors, organizational practices, and environmental conditions in maritime safety. Furthermore, the model's focus on dynamic and real-time data integration advances the traditional static models used in maritime risk assessments, offering a more nuanced and immediately applicable approach to accident prevention.

Based on the insights gained from the DAN model, several recommendations proposed as follows.

- Enhanced training and resting hour practices: Implementing comprehensive training programs that focus on fatigue management and stress reduction can mitigate human error. Additionally, enforcing strict adherence to rest period policies will help reduce fatigue-related accidents.

- Improving safety culture and oversight mechanisms: Organizations should strive to maintain an optimum safety culture and robust oversight mechanisms to ensure adherence to safety protocols and procedures.
- Equipment maintenance and technological upgrades: Regular maintenance and technological upgrades of navigational and operational equipment are crucial to prevent technical failures.
- Real-time traffic management: VTS operators should utilize real-time data provided by models like DAN to manage traffic dynamically, especially during peak times or adverse conditions.

8. Areas of practical applications

The DAN model, developed for assessing and mitigating risks in high-traffic maritime areas, offers several practical applications that significantly enhance safety and operational efficiency. These applications make the model an invaluable decision-support tool for various maritime stakeholders, particularly in managing congested and complex navigational environments. As exemplified below the model can be utilized as a decision-support system to enhance navigational safety by identifying risk patterns and suggesting preventative measures in critical maritime areas (i.e. narrow waterways, congested coastal areas, traffic separation scheme areas, port approaches).

Real-time risk assessment: The DAN model provides a dynamic and real-time assessment of risks based on current environmental conditions, vessel characteristics, and human factors. This feature allows Vessel Traffic Service (VTS) operators and ship navigators to continuously monitor risk levels and make informed decisions promptly. For example, the model can predict the increase in collision risk due to a sudden change in visibility or traffic density, enabling proactive management.

Pilotage, tug assistance, or similar preventive measures: Based on the assessed risks, the DAN model can recommend specific preventive measures to mitigate potential hazards. For instance, it might suggest the engagement of pilot services for vessels entering narrow passages or the use of tug assistance for large vessels under poor maneuverability conditions. These recommendations are tailored to the specific scenarios and conditions assessed, ensuring that measures are both timely and relevant.

Suspensions of transit: In scenarios where the risk level exceeds a predefined safety threshold, the model can advise on the suspension of transits. This application is particularly crucial during extreme weather conditions, high traffic congestion, or when critical navigational aids are compromised. Such suspensions prevent accidents by avoiding the escalation of hazardous situations, thereby safeguarding both human life and environmental integrity.

The model's ability to adapt to various maritime environments and its capacity for real-time data processing make it a valuable tool for contemporary maritime risk management. However, while the DAN model marks an advancement in the field, it is not without its limitations. One such limitation is the treatment of human factors; although the model incorporates elements like fatigue and stress, these inputs are often based on static data, which may not adequately reflect the dynamic nature of human behavior and condition changes over time. Additionally, the model's focus on pilotage and tug assistance is somewhat limited. It provides general recommendations that may not take into account the specific regulations of individual ports or the unique characteristics of different vessel types and sizes.

To address these limitations and enhance the model's utility, several areas of future development are suggested.

- Integration with artificial intelligence (AI) and Wearable Technology for Real-Time Data Input: Future iterations of the DAN model could incorporate artificial AI and wearable technology to collect and analyze real-time data. This would enable more accurate monitoring of human factors, such as crew fatigue and stress levels, by continuously updating the model with real-time physiological and behavioral data from crew members. Enhancements like these would not only enhance the precision of risk assessments but also facilitate more tailored safety measures.
- Expansion to Other Maritime Zones and Varying Operational Scenarios: It is proposed to expand the model's applicability to encompass a broader range of maritime environments and operational scenarios, including ice-covered waters, areas with restricted visibility, or regions with unique ecological or traffic concerns. By broadening the scope of the model to these varied conditions, its relevance and utility as a comprehensive tool for global maritime operations would be significantly increased.
- Enhancements for Autonomous Vessel Operations (D1-D4 Phases): As the maritime industry moves towards increased automation, the DAN model could be refined to better support operations of autonomous vessels across different levels of autonomy (D1-D4 phases). This adaptation would involve addressing the distinct challenges of autonomous navigation, such as algorithmic decision-making, sensor reliability, and interactions between machines and humans during mixed operations. Potential enhancements could include developing specific risk assessment modules tailored to the technological and operational levels of autonomous vessels.

10. Conclusion

This study aimed at contributing to the field of maritime safety and risk management through the development and application of the DAN model. The integration of the Human Factors Analysis and Classification System (HFACS) with Bayesian Networks has enhanced the model's predictive capabilities. This integration allows for a comprehensive analysis of the causal factors leading to marine casualties and incidents, incorporating both human and operational elements. The model predicts potential accidents by analyzing dynamic interactions among these factors, offering a nuanced approach to risk assessment and enhancing safety across various maritime zones, including narrow waterways, Traffic Separation Scheme (TSS) areas, and port approaches.

The practical implications of the DAN model for maritime safety and operational planning are notable. It can support strategic decision-making by vessel traffic service (VTS) operators and maritime navigators, enabling them to proactively manage risks and prevent accidents. Additionally, the data provided by the model can inform policy formulation, aiding in the development of regulations that enhance maritime safety, such as mandatory pilotage in high-risk areas or improved training protocols for crew members. By identifying high-risk factors and conditions, the model aims to assist maritime authorities in effectively allocating resources to deploy safety measures where they are most needed. To maximize the efficacy and applicability of the DAN model, collaboration among maritime authorities, researchers, and industry stakeholders is essential. Such collaboration will refine and adapt the model to meet the evolving challenges of maritime safety and extend its application to more diverse environments and emerging maritime technologies. This study highlights the importance of risk management tools, and the collaborative efforts required to safeguard maritime domains amidst increasing complexities, thereby promoting a more unified approach to global maritime safety.

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4. A Novel Solution for Retrospective Enhancement of Passenger Vessel Damage Stability

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Abstract: Ship flooding and inadequate damage stability remains the greatest risk to life in the maritime industry today. To address this problem, increasingly stringent damage stability regulations have been introduced at the international level, most recently SOLAS 2020. However, these apply only to new vessels, leaving the majority of the global fleet under older, more lenient regulations. In fact, the effect of these regulatory changes won't be fully realized for 30-40 years, when older ships are phased out, and that is a long time to wait. The challenge lies in the difficulty and cost of retrofitting older ships to meet modern standards. Adding to the problem is the tendency for the stability of vessels to deteriorate over time, meaning the situation is liable only to get worse. At the heart of the issue has been an overreliance on subdivision as the primary method of controlling flooding, which is exceedingly hard to retrofit in older ships and has diminishing returns with increased application. This highlights the need to seek alternative means of improving damage stability for both new and existing vessels. The research presented in this paper proposes a novel solution to this problem, namely the use of high-expansion polyurethane foam as a means of reducing vessel permeability and enhancing survivability. The system is easy to apply, making it suitable for both new and, more importantly, older ships. The paper provides an overview of the development process to date and presents a methodology for implementing the solution on ships, culminating with promising results from a recent impact assessment conducted on an existing RoPax vessel.

Keywords: Damage stability; Risk-based design; Flooding risk; Passenger vessel safety; Ship survivability

1. Introduction

Despite considerable advancements in ship design and safety, inadequate damage stability remains the greatest singular risk factor within the maritime industry. Observing casualty statistics over the past nine years highlights that ship flooding is responsible for over 50% of all reported losses (Allianz, 2025), indicating that this one risk factor accounts for more casualties than all other significant contributing factors combined. This alarming trend has rightfully prompted international regulatory bodies to implement more stringent safety standards, most recently adopting the SOLAS 2020 amendments (IMO, 2020). However, the efficacy of these new regulations is inherently limited by their scope, as they apply exclusively to newly constructed vessels. This creates a significant and ever-widening safety gap between new build designs and the substantial population of existing ships (Cichowicz et al., 2016;

Dankowski and Krüger, 2011; Person, 2019; Vassalos et al., 2016). Vessels designed and built to previous, less stringent stability standards, may reasonably expect to remain in active service for another 30 years or more (Dinu and Ilie, 2015). Consequently, the full, transformative impact of modern regulatory improvements will not be truly realized until these older vessels are gradually phased out of operation.

Compounding this challenge is the often-overlooked reality that ship stability inherently deteriorates with age. This degradation can generally be attributed to numerous modifications and upgrades undertaken throughout a vessel's operational life. Such alterations, particularly those involving the addition of weight high within the vessel structure, invariably lead to an increase in the vertical center of gravity (VCG) and a subsequent reduction in metacentric height (GM). This often means that older vessels not only fail to comply with current, more demanding stability regulations, but are also at genuine risk of falling out of compliance with the more lenient regulatory frameworks in force at their inception.

Figure 1 illustrates a compelling example of the lifecycle weight growth, presenting a time history of a cruise ship's weight as recorded during successive lightweight surveys from its launch date through to its most recent survey in 2020. This data clearly highlights a significant increase in the vessel's lightship weight, rising from an initial 49,700 tonnes to 51,470 tonnes. This substantial growth demonstrates the considerable potential for weight accumulation over a vessel's operational lifespan.

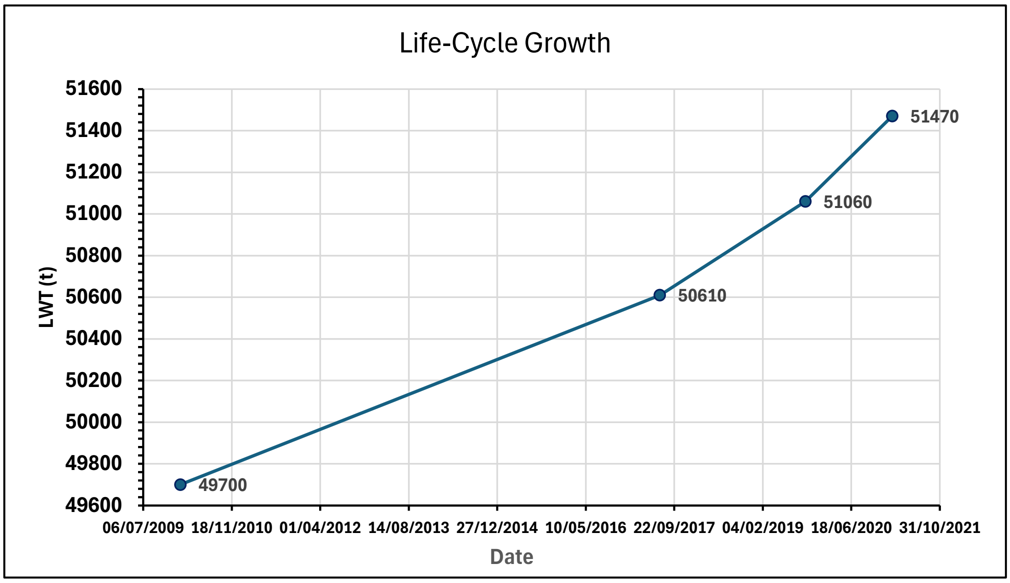

Figure 1: Life-Cycle Growth Example for a Large Cruise Vessel

Figure 2, presented below, provides a critical insight into how this additional weight directly impacts the vessel's vertical center of gravity (VCG). Following the same time history and derived from inclining tests conducted concurrently with the lightweight surveys, the figure reveals a rise in VCG from 19.8 meters to 20.0 meters. While this 20 cm change might on the surface appear small, it is tremendously significant in the context of ship stability, often translating into a considerable reduction in metacentric height (GM) and, consequently, a substantial decrease in the vessel's stability margins.

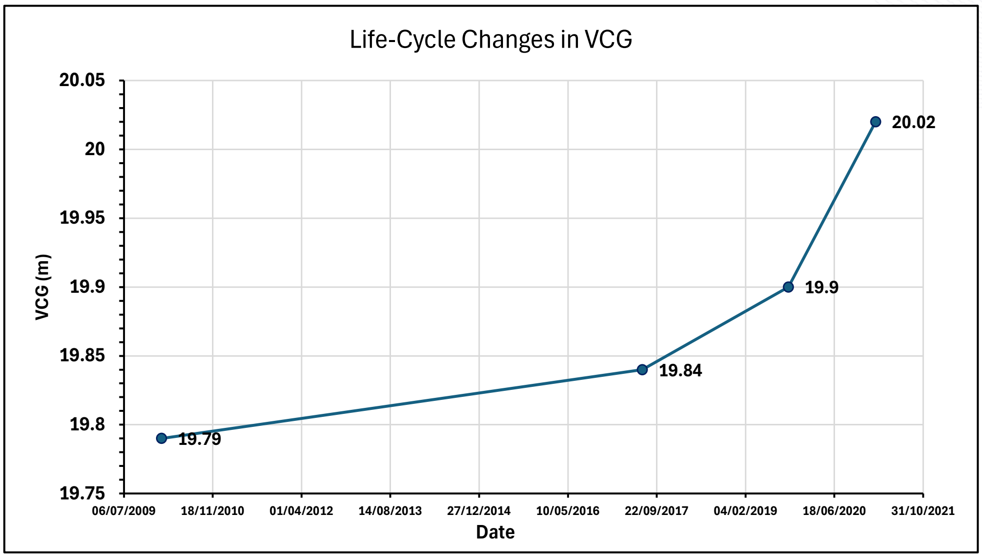

Figure 2: Impact of Life-cycle Growth on VCG

In acknowledgement of the extensive stability deterioration that can occur over a ship's life-cycle, modern passenger vessels are now typically designed with more significant stability margins in an effort to "future-proof" designs against life-cycle growth. Unfortunately, many existing ships were not designed with this foresight, meaning they now require significant and often costly upgrades to remain compliant. These upgrades, while essential for enhancing safety, frequently impact the operability of the vessel and can limit payload capacity, thereby affecting the economic viability of continued operation. The reason for this further derives from the fact that the options available to naval architects and designers in addressing fundamental stability deficits in existing vessels are inherently limited (Bačkalov et al., 2016; Boulougouris et al., 2016; Vassalos and Paterson, 2020). Constrained by the fixed hull form and internal arrangements of a pre-existing vessel design, solutions often resort to brute-force methods such as adding significant quantities of fixed ballast or undertaking extensive and disruptive structural modifications. These interventions are capital-intensive, time-consuming, and invariably impose operational penalties on the vessel as discussed further in the following section.

2. Issues with existing solutions

While the imperative to enhance the damage stability of older passenger vessels is clear, the existing retrospective solutions available are far from ideal. The significant constraints of modifying a pre-existing hull form and internal structure mean that designers are faced with a narrow design space within which to find solutions, and often considerable compromises must be made.

One common approach involves the addition of semi-watertight doors. These doors are designed to be watertight up to a limited head of water, offering a degree of floodwater containment. However, their effectiveness often necessitates the upgrade of numerous doors throughout the vessel, leading to significant installation costs and logistical challenges. Crucially, they demonstrably affect operability, impeding the free flow of passengers and crew and complicating emergency evacuation procedures. Furthermore, their ability to limit floodwater is restricted to relatively low collapse heights, typically around 3 meters water head (Jalonen et al., 2012; Veritas et al., 2009), resulting in only marginal improvements in overall damage stability.

Another option is the installation of sills, either fixed or tiltable, which act as partial watertight barriers to limit the progression of flooding. These are often located at the foot of doorways or around the upper boundaries of stairwells, though they are sometimes found in corridors as well. These barriers are generally limited in height, often only up to 30 cm, rendering them ineffective against significant ingress of water. Their practical utility is further compromised in dynamic sea states where the pumping action of a vessel rolling in waves can easily overcome these low barriers. This highlights a critical disconnect between their theoretical benefit in hydrostatic damage stability calculations (which are inherently blind to dynamic effects) and their actual efficacy in real-world scenarios. Consequently, these measures tend to yield improvements that are questionable in reality.

The use of permanent ballast, whether solid or liquid, is a fairly straightforward method to lower the vessel's vertical center of gravity (VCG). While conceptually simple, adding significant quantities of ballast increases the vessel's overall weight and draft, thereby lowering its freeboard and reducing its payload capacity. Furthermore, there must be the space available to house the ballast. For this reason, it is often viewed as a method of last resort.

The retrofitting of sponsons involves welding additional watertight structures to the stern or sides of the ship to increase its initial stability (GM). While effective in principle (Vainionpää, 2022) (Vassalos et al., 2015), sponsons represent a costly and complex installation, often requiring extensive dry-docking periods. They inevitably increase the ship's weight and can negatively impact resistance, leading to higher fuel consumption and reduced speed. Critically, their presence can paradoxically worsen damage stability in scenarios where the sponsons themselves are breached, creating additional compartments that flood asymmetrically and further compromise the vessel's stability.

Perhaps the most traditional and effective form of flooding protection is the installation of additional watertight subdivision. This can take the form of conventional fixed bulkheads or flood control barriers such as those offered by MacGregor and applied to subdivide Ro-Ro decks. While fixed bulkheads are theoretically highly effective at localising floodwater, their retrospective application is fraught with difficulties (Vassalos and Paterson, 2020, 2021). Gaining accessibility to install new steel plating below the bulkhead deck often necessitates cutting through existing structural elements, a highly disruptive and costly process. Furthermore, the limited free space within an operational ship is a significant impediment; machinery, pipe runs, cables trays and ventilation ducts frequently occupy most available volume, leaving little room to accommodate new bulkheads. These additions also inherently add weight to the vessel and can significantly influence the ergonomics and operational flow depending on their placement, impacting passenger and crew movement. While flood control barriers offer a less invasive alternative for Ro-Ro decks, they do present operational difficulties regarding the loading of the vessel as certain areas of the deck must be kept clear to accommodate the barriers (Santos, 1999).

The common theme among these existing retrospective solutions is their fundamental inadequacy. They are often highly invasive, impose significant operational penalties, are financially burdensome, and ultimately offer only limited enhancements to a vessel's overall damage stability performance. This pervasive lack of truly effective and practical options underscores the urgent and growing need for the maritime industry to actively seek and develop novel and alternative solutions to address the critical safety gap for its aging passenger vessel fleet.

3. Proposed solution

In light of the limitations in conventional retrospective damage stability enhancements, this paper proposes a novel and non-invasive solution, namely the strategic filling of high-risk void spaces within existing vessels with high-expansion polyurethane foam. This approach targets spaces that are typically inaccessible or unused, such as cofferdams, double bottom tanks, and other structural voids, thereby ensuring that the solution does not heavily impact the day-to-day operation of the vessel, nor rob the utility of any actively used spaces. Similar approaches have been proposed over recent years, originating with a suggested system that would actively deliver the foam to the damaged compartment following a breach (Vassalos et al., 2016). This was further developed into a passive system whereby empty void space(s) were permanently filled within foam material (Valanto, 2022; Vassalos and Paterson, 2020, 2021; Vassalos et al., 2022).

The fundamental principle behind the foam's effectiveness lies in its ability to significantly reduce the permeability of the targeted void space. In a damage scenario, instead of floodwater being allowed to fully enter and occupy the compromised volume, the foam mass effectively blocks and displaces the ingress of water. This contrasts sharply with traditional subdivision, which primarily seeks to contain water once it has already entered the vessel. By preventing the initial entry of a substantial volume of floodwater, the solution inherently limits lost buoyancy and minimizes free surface effects that are detrimental to stability. Moreover, the foam itself acts as a buoyant volume, providing additional floatability and enhancing the residual stability of the vessel following damage. This innovative approach offers a promising pathway to retrospectively enhance damage stability without incurring the severe operational and financial penalties associated with conventional methods.

The specific properties of the high-expansion polyurethane foam are critical to its efficacy. This material is produced by mixing a resin and a hardening agent, which initiates an exothermic reaction resulting in rapid foam expansion. The foam utilized in this proposed solution boasts an impressive expansion ratio of 1:40, meaning it expands to 40 times its original liquid volume, effectively filling large void spaces from minimal initial quantities. The resultant solid foam possesses a remarkably low density of approximately 25 kg/m^3, minimizing any significant weight addition to the vessel. Crucially, the foam is characterized by its closed-cell structure, rendering it non-porous and thus near impermeable to water, as outlined later within the paper. Furthermore, the material is inert and not subject to deterioration over time, ensuring its long-term effectiveness as a passive flood protection measure.

4. Methodology

The research methodology applied within this paper is primarily focused on verifying the efficiency and suitability of high-expansion polyurethane foam as a retrospective damage stability enhancement. This verification process involved a comprehensive series of experimental investigations into the foam's material properties, followed by a detailed numerical case study on an existing RoPax passenger vessel.

Firstly, to address the crucial question of the foam's resistance to water ingress, a series of water absorption tests were conducted. Specimens of the foam material were immersed in water, and their weight was monitored over a period of 30 days. Any detected weight increase was directly correlated to absorbed water mass, thereby allowing for the determination of the foam's permeability. Recognizing that floodwater can exert significant hydrostatic pressure on the foam mass within a damaged compartment, these tests were performed at varying external pressure, firstly at atmospheric pressure, and subsequently within a pressure vessel at 0.5 bar, 1 bar, and 1.5 bar, respectively. This comprehensive pressure regime accounts for potential water columns up to 15 meters, providing a realistic assessment of the foam's integrity under flooding conditions.

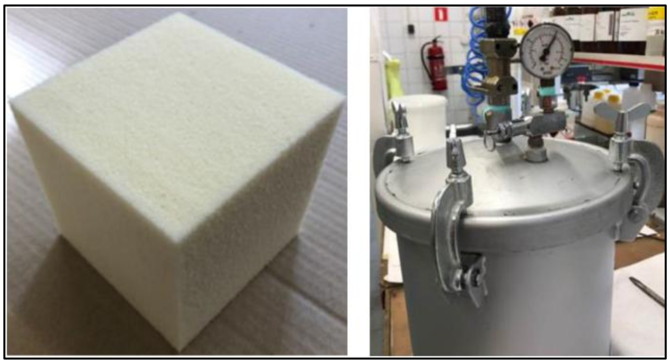

Figure 3: Foam test specimen shown left, pressure vessel shown right.

Next, the adhesion and cohesion properties of the foam were ascertained to determine its ability to remain securely in place when subjected to the dynamic forces associated with a flooding scenario. A stud pull test, as detailed in Figure 4, was performed on foam specimens formed directly onto both bare and painted steel plates, mimicking typical shipboard surfaces. This test provided valuable data on the bond strength between the foam and structural elements, which is vital for ensuring it will not be displaced from its installation position.

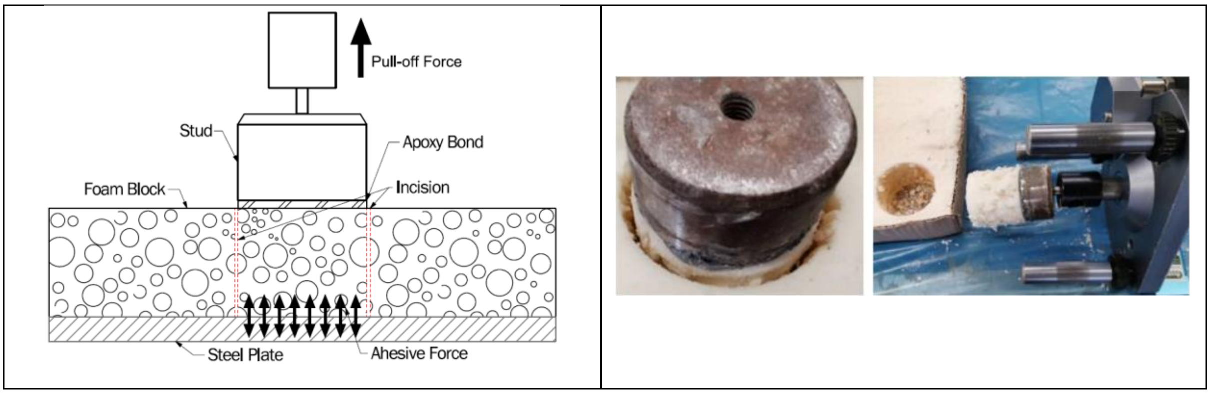

Figure 4: Outline of stud pull test

The potential for the foam to be compressed by the hydrostatic head of floodwater was investigated through compression testing, as illustrated in Figure 5. Foam specimens were subjected to axial loading in a universal testing machine to generate the material's stress-strain curve. This characterization allowed for a direct comparison between the foam's compressive strength and the expected compression forces it would experience following a flooding event, ensuring that the buoyant volume provided by the foam would not be significantly diminished under pressure.

Figure 5: Pictorial image of foam compression test

Given the organic nature of polyurethane, its combustibility is a critical safety consideration. Adhering to the principle of not resolving one problem by inadvertently introducing another, the foam technology was subjected to a rigorous series of fire tests, some out which are illustrated in Figure 6. Many of these tests were conducted in accordance with the IMO FTP Code (IMO, 2012) at an approved, independent laboratory, DMT in Germany. These comprehensive assessments included thermal decomposition tests, smoke and toxicity tests, thermal conductivity tests, and overpressure testing, all aimed at evaluating the foam's fire performance and ensuring its compliance with maritime safety regulations. Though not further elaborated upon within this paper, further details of the fire testing procedures that have been conducted on the foam technology may found in (Vassalos et al., 2022).

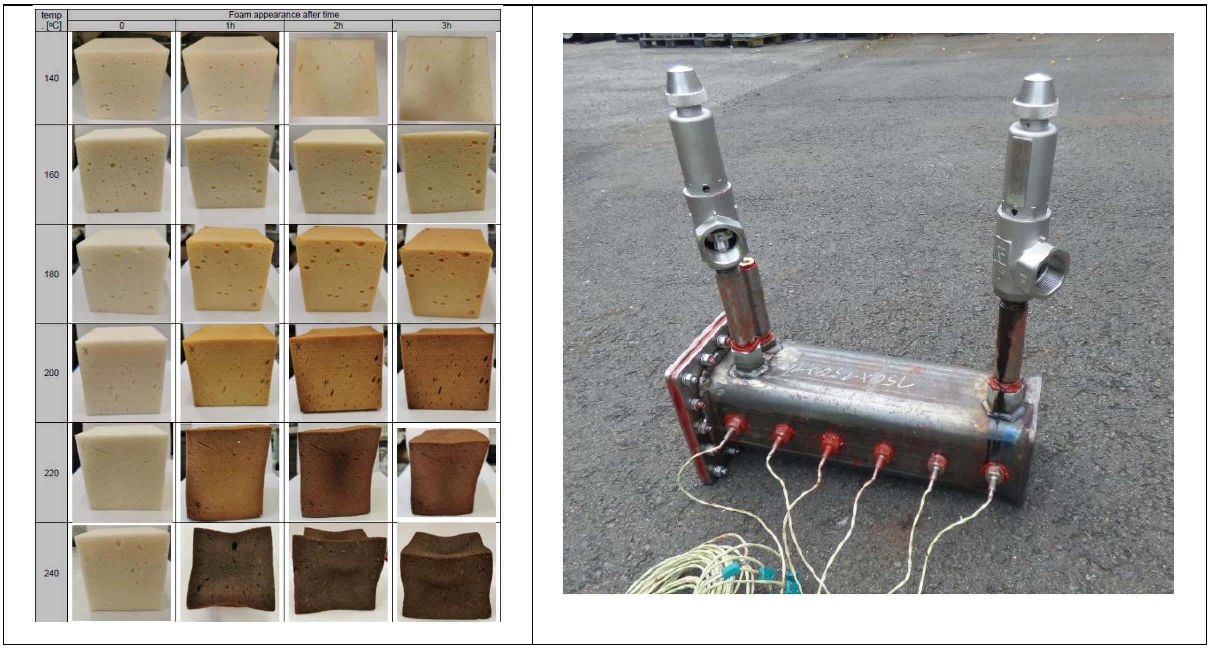

Figure 6: Visual results from foam thermal decomposition test (left), over pressure testing apparatus (right).

Finally, to evaluate the practical efficacy of the proposed solution, an existing RoPax vessel design was utilized as a detailed case study. This vessel was subjected to probabilistic damage stability calculations in full accordance with the current SOLAS 2020 regulations (IMO, 2020). An initial damage stability calculation was first conducted on the as-designed vessel to establish a baseline. Subsequently, a risk-profile was generated by mapping the flooding risk across the vessel's various compartments. This detailed profile served as the basis for strategically determining the optimal placement of the foam solution, targeting areas identified as having heightened vulnerability to flooding. The foam solution was incorporated into the stability model by representing it as a reduction in space permeability within the relevant compartments. The optimal volume of foam to be employed was then determined through a sensitivity analysis, investigating the incremental increase in vessel survivability relative to the volume of foam installed. The derived optimum foam volume was then used to conduct the final damage stability analysis, from which the potential benefits and overall enhancement in vessel safety attributable to the proposed solution could be quantitatively gauged.

5. Foam testing results

5.1 Determining foam permeability

The water absorption tests conducted to ascertain the permeability of the foam material yielded unexpected yet significant findings. Surprisingly, the largest degree of water absorption was observed when the foam specimens were tested under atmospheric pressure conditions, with 2.7% of the volume being occupied by water following 28 days exposure, as shown Figure 7Figure 7.

Conversely, when subjected to the overpressure conditions (0.5 bar, 1 bar, and 1.5 bar) also analyzed, an interesting phenomenon was observed. The outer layer of the foam material underwent a structural collapse of its surface bubbles. This collapse, rather than leading to increased absorption, acted to form a protective "shield" or barrier, effectively preventing any further water absorption. This self-sealing characteristic under pressure is a highly advantageous property for a flood mitigation material.

A considerable effort was dedicated to optimizing the foam formula to achieve an ideal balance between low density and its propensity to absorb water. It was consistently found that lower-density foams, while offering the benefit of reduced weight, exhibited a higher permeability, which unfortunately offset the advantages of a lighter material. Furthermore, these lower-density formulations also displayed negatively affected compressibility properties, meaning they were more prone to unwanted volume reduction under hydrostatic pressure. This extensive material science investigation was crucial in developing a foam variant that maximizes both buoyancy and resistance to water ingress while minimizing weight implications.

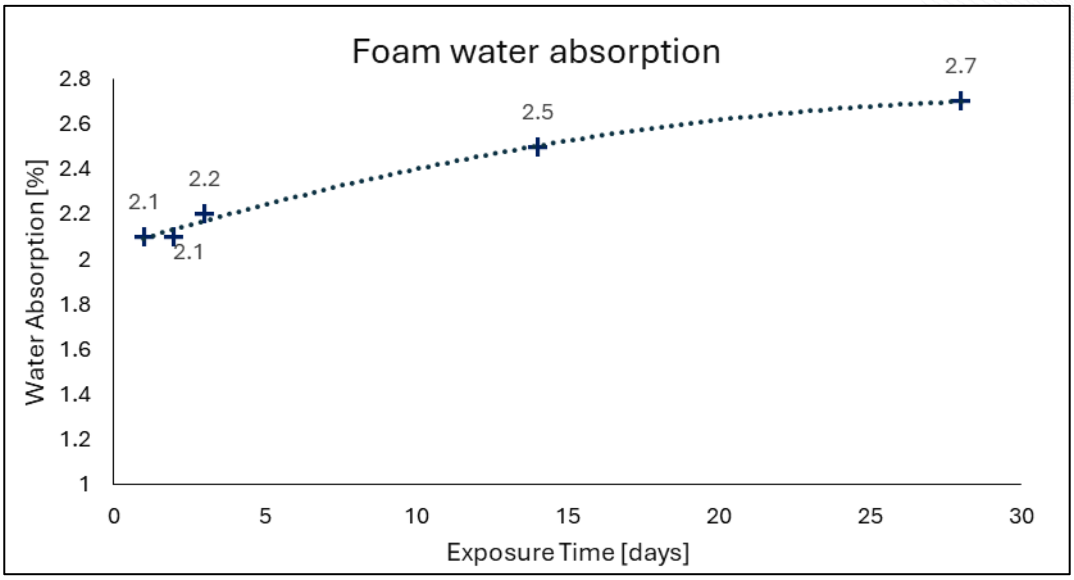

Figure 7: Foam Water Absorption Test Result at Atmospheric Pressure

5.2 Foam adhesion & cohesion properties

The crucial aspect of the foam's ability to remain securely in place during a dynamic flooding event was assessed through a series of adhesion and cohesion tests. The results of these experiments were highly encouraging, demonstrating robust material properties. Cohesion, which represents the internal strength of the foam itself, was consistently found to be higher than its adhesive properties. The measured values were:

- Adhesion: 0.13 MPa
- Cohesion: 0.19 MPa

To put these figures into a practical context, these results mean that a force of approximately 13 tonnes would be required to separate a segment of foam with a 1 m^2 contact area from a steel surface. Such magnitudes of force are far beyond any expected to act upon the foam in a real-world flooding scenario. Therefore, these tests provide strong assurance that the foam will remain firmly in place within the void spaces, offering continuous buoyant support and floodwater exclusion even under the most severe conditions.

5.3 Foam compressibility properties

The compression tests conducted on the foam material provided critical insights into its structural integrity under simulated floodwater pressures. The results demonstrated that the elastic deformation region of the foam extends up to 0.22 MPa. Beyond this point, plastic deformation is realized, occurring at approximately 5% volumetric compression, Figure 8.

Significantly, the expected compression resulting from exposure to the hydrostatic pressure in a flooding scenario is conservatively estimated at 0.1 MPa. This anticipated pressure would lead to a compression of approximately 3%. This level of compression is well within the foam's elastic range and, crucially, does not jeopardize the buoyancy offered by the foam to any significant degree, affirming its ability to maintain its volume and provide effective support even when subjected to the substantial forces of floodwater.

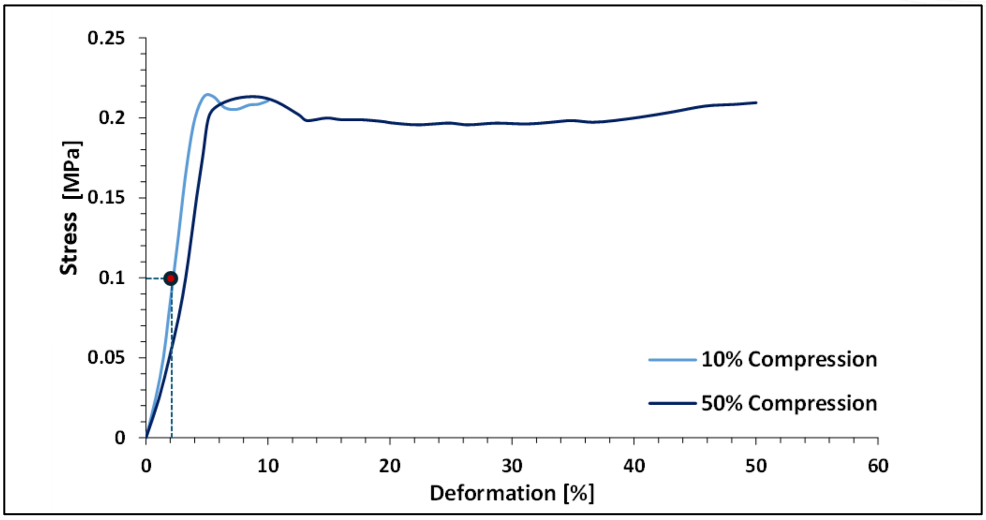

Figure 8: Foam Compressibility Results at 10% and 50% compression

6. Impact assessment – RoPax vessel case study

6.1 Overview of case study vessel properties

To evaluate the practical applicability and efficacy of the proposed foam-based solution, a detailed case study was conducted on an existing large RoPax vessel. This particular vessel, approximately 15 years in age, was designed and built in accordance with the SOLAS 2009 regulations, making it a representative example of the older passenger fleet that faces increasing damage stability challenges. The vessel has a substantial passenger capacity of approximately 2,400 persons and features three Ro-Ro decks, one of which is a mezzanine deck. Its internal volume is subdivided into 17 watertight compartments.

The vessel hull form is illustrated in Figure 9 and the key properties of the subject vessel are detailed in Table 1.

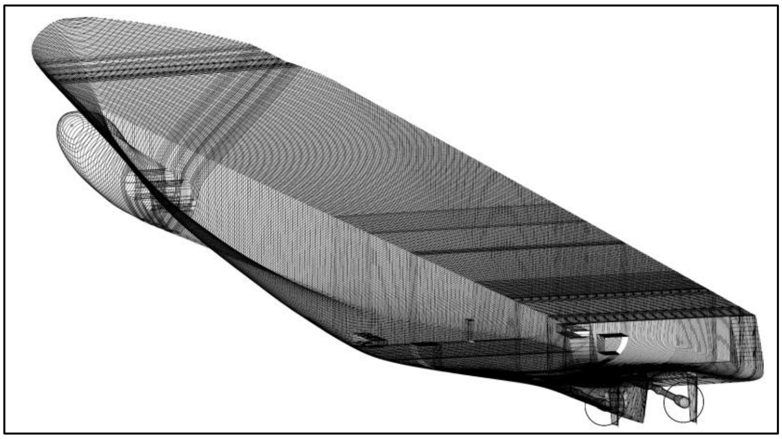

Figure 9: Stability Model Calculation Sections

Table 1: Vessel Particulars

Principle Particulars	
Length OA	≃210 m
Length BP	≃195 m
Length WL	≃200 m
Breadth, molded	≃25 m
Draught, design	6.55 m
Draught, scantling	6.70 m
Draught, subdivision	6.70 m

6.2 Assessment of as-built damage stability performance

6.2.1 Statutory damage stability analysis results

An initial damage stability assessment was conducted on the case study RoPax vessel to establish a baseline performance against the regulatory framework under which it was originally designed and built, namely SOLAS 2009 (IMO, 2009). The probabilistic damage stability calculations were performed in accordance with the methodologies prescribed by these regulations.

The results of this baseline assessment are presented in Table 2 which details the partial Attained Subdivision Indices for each of the three calculation draughts, along with the final Attained Subdivision Index (A) calculated as the weighted sum of these partial indices.

Table 2: As-Built Damage Stability Results in Accordance with SOLAS 2009

Draught (m)		Intact GM (m)	Trim (m)	Partial Indices		Attained Index	
Dl	5.807	1.78	-0.35	Al	0.793	0.2	0.1586
Dp	6.343	1.905	0.00	Ap	0.796	0.4	0.3184
Ds	6.700	2.26	0.00	As	0.792	0.4	0.3171
Required Subdivision Index R							0.7911
Attained Subdivision Index A							**0.7943**

As demonstrated by the results in Table 2, the vessel marginally surpasses the Required Subdivision Index (R) under SOLAS 2009, achieving an Attained Index (A) of 0.7943 against a Required Index of 0.7911. As expected, this indicates that the vessel meets the minimum damage stability criteria of its applicable regulatory period.

However, it is critically important to note the implications of evolving safety standards. This vessel, designed to SOLAS 2009, would not meet the more stringent requirements of SOLAS 2020, which mandates a significantly higher Required Subdivision Index of 0.845. This stark disparity clearly highlights the "safety gap" between existing older vessels and newly constructed tonnage, underscoring the pressing need for retrospective solutions to enhance the damage stability performance of the older fleet.

6.2.2 Vessel risk profile

Building upon the initial damage stability assessment, a flooding risk profile for the RoPax vessel was generated. This profile provides a graphical depiction of flooding risk distributed along the entire length of the vessel. In Figure 10, the X-axis denotes the damage longitudinal center, while the Y-axis represents the calculated flooding risk, defined as the probability of damage multiplied by the complement of ship survivability (i.e. capsize probability).

The analysis of this risk profile clearly indicates that the vessel exhibits areas of heightened risk in its aft and fore shoulders. This observation aligns with typical findings for passenger vessels, where the geometry and internal arrangements in these regions often contribute to a greater susceptibility to critical flooding. Consequently, compartments located within these high-risk zones should be specifically targeted for the application of the foam solution, contingent upon the operational nature and accessibility of the spaces within these areas. This risk informed approach ensures that the retrospective enhancement is applied where it will yield the most significant improvement in overall vessel safety.

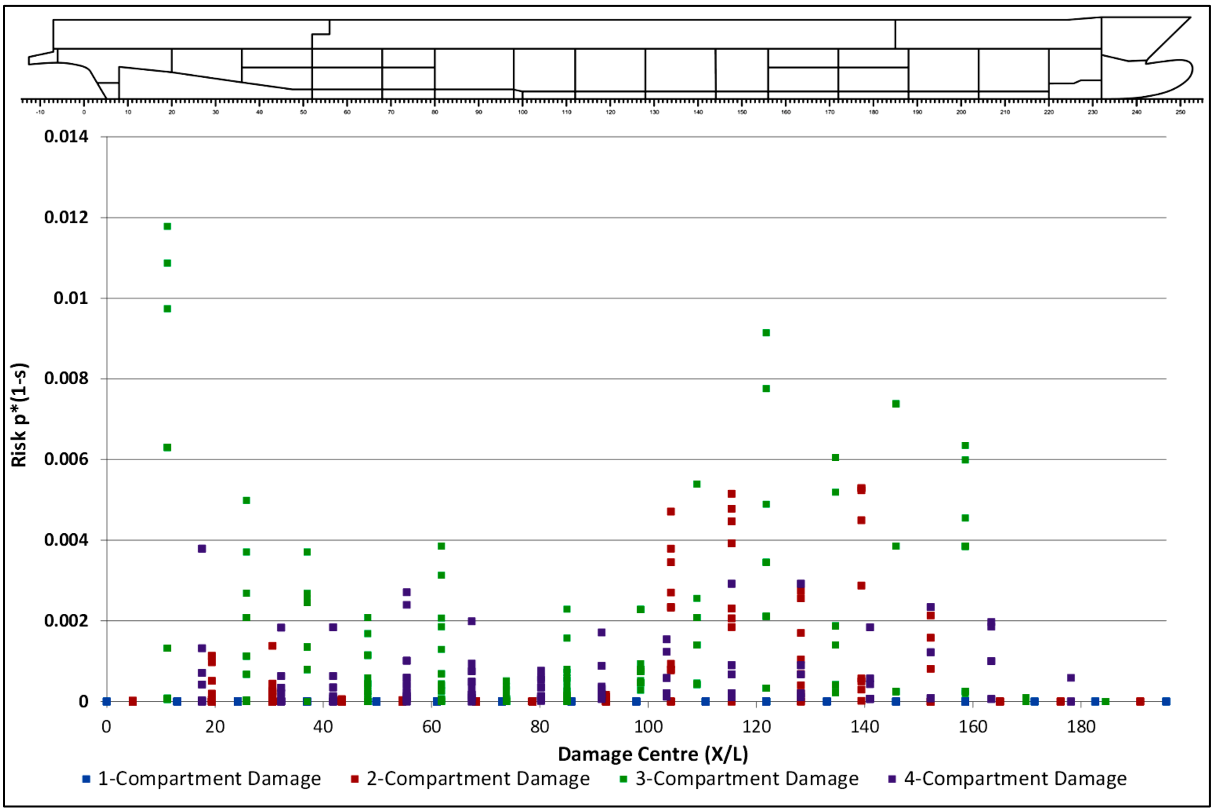

Figure 10:As-Built Risk Profile

6.2.3 Selection of spaces for foam application

Using the insights gained from the vessel's risk profile, the identification of suitable void spaces for foam application proceeded. Fortunately, the areas previously determined to have heightened flooding risk, specifically the fore and aft shoulders of the vessel, also contain a number of dry tanks and other void spaces. These spaces are ideal candidates for the proposed solution as their utilization for foam filling will not interfere with the vessel's operational areas or passenger amenities.

In total, three void spaces have been strategically targeted for foam application: two spaces situated around the vessel's fore shoulder and one space located within the vessel's aft shoulder.

Figure 11 highlights the location of these selected compartments within the vessel's general arrangement, shaded in blue. This targeted approach ensures that the foam is deployed in locations that offer the maximum benefit in enhancing the vessel's damage stability performance.

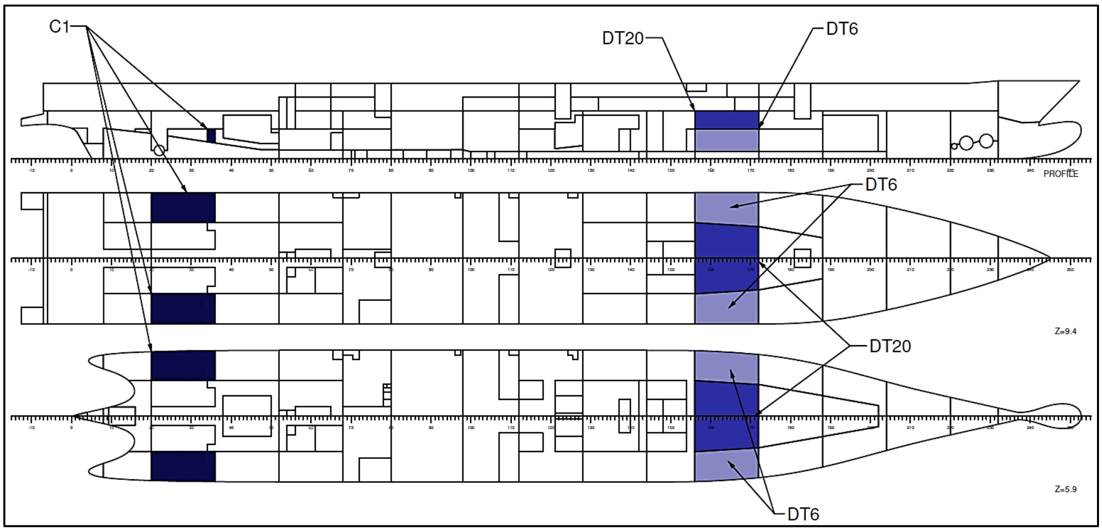

Figure 11: Spaces Targeted for Foam Application

6.2.4 Implementation of foam application

A critical step in the implementation of the proposed solution involved identifying the optimal foam volumes to be introduced into each of the three targeted void spaces. This was achieved through a comprehensive sensitivity analysis for each compartment, where the decrease in vessel flooding risk was evaluated against varying percentages of foam fill.

As an illustrative example of this process, Figure 12 demonstrates the results of the sensitivity analysis for one of the selected spaces. This figure clearly indicates a trend of diminishing returns in terms of increased survivability beyond approximately 70% of the space being filled with foam. This threshold suggests that beyond a certain point, the marginal benefit of adding more foam becomes less significant relative to the increased cost and weight.

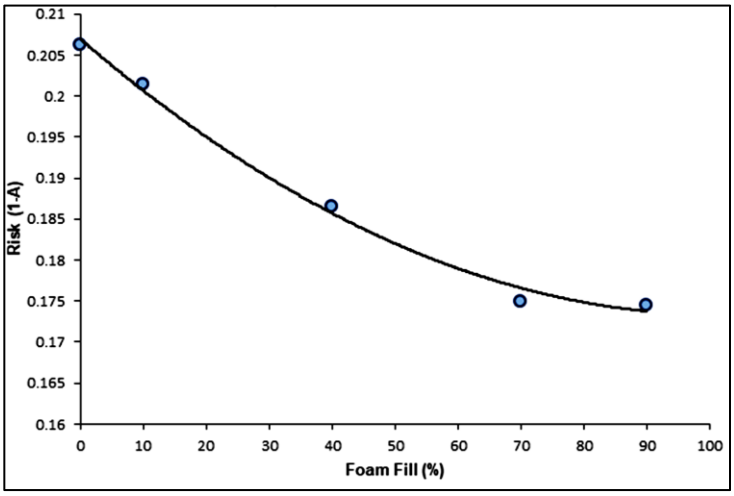

Figure 12: Sensitivity Analysis of Foam Volume and Flooding Risk Reduction

Following this analysis for each of the three targeted compartments, the optimal foam volumes were determined, ensuring the most efficient and impactful application of the solution. These optimal volumes for each space are summarized in Table 3 below.

Table 3: Summary of Optimal Foam Volumes

Compartment ID	Foam Volume (m^3)
C1	560
Dry Tank No 6	900
Dry Tank No 20	400

7. Evaluation of foam solution impact on survivability

With the optimal foam solution identified and modelled, the vessel's damage stability performance was reassessed to quantify the impact of the proposed enhancement. Probabilistic damage stability calculations were conducted once again, incorporating the reduced permeability in the foam-filled void spaces.

The results of this re-assessment are presented in Table 4, showing the partial Attained Subdivision Indices for each of the three calculation draughts, along with the updated final Attained Subdivision Index.

Table 4: Damage Stability Results with Foam Solution in Accordance with SOLAS 2009

Draught (m)		Intact GM (m)	Trim (m)	Partial Indices		Attained Index	
Dl	5.807	1.78	-0.35	Al	0.793	0.2	0.176
Dp	6.343	1.905	0.00	Ap	0.796	0.4	0.348
Ds	6.700	2.26	0.00	As	0.792	0.4	0.341
Required Subdivision Index R							0.791
Attained Subdivision Index A							0.865

The results demonstrate a significant improvement in the vessel's damage stability. The Attained Subdivision Index has risen from its previous value of 0.7943 to 0.865. While this numerical difference of approximately 0.07 might appear small, in the highly sensitive domain of damage stability, this represents a tremendous enhancement in survivability.

Crucially, and perhaps most significantly, the vessel would now comply with the rigorous requirements of SOLAS 2020, as its new Attained Index of 0.865 comfortably exceeds the required value of 0.845. This outcome underscores the potential of the foam solution to bridge the safety gap for older passenger vessels, offering a viable and effective means of retrospective compliance with modern damage stability standards.

To further illustrate the profound impact of the foam solution, a side-by-side comparison of the vessel's risk profiles, both pre- and post-application of the foam, is presented in Figure 13. Here, it can be observed that the high-risk areas previously identified in the vessel's aft and fore shoulders have undergone a significant reduction in flooding risk. In several instances, the risk has been effectively eradicated in these targeted zones. This underscores the ability of the foam solution to directly mitigate the most critical vulnerabilities within the vessel, transforming areas of high susceptibility into zones of considerably enhanced safety.

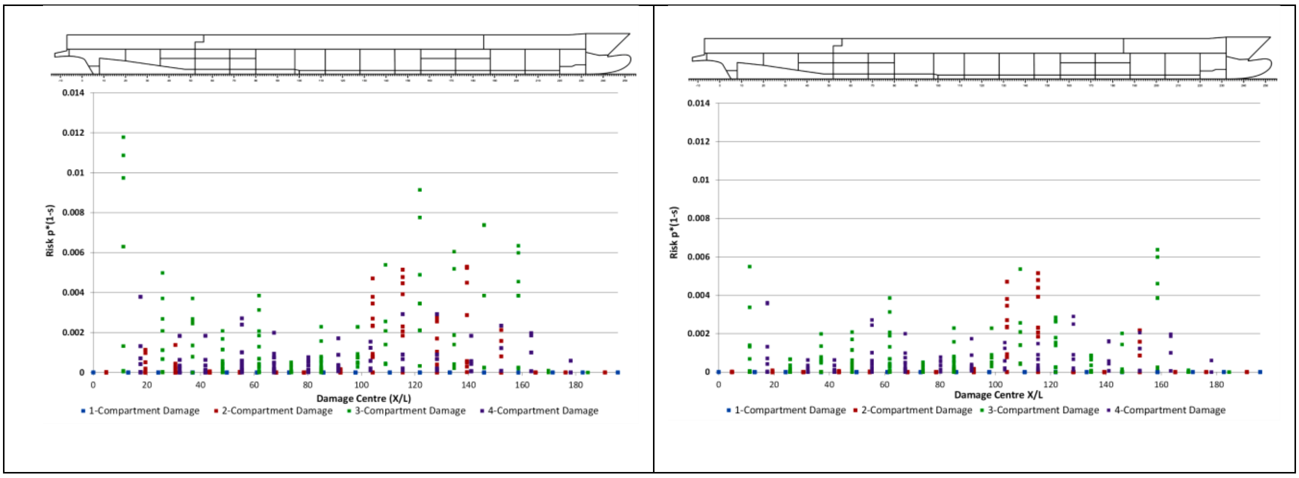

Figure 13: Comparison of Risk profiles, as built design shown left, modified design shown right

8. Conclusions

In conclusion, the application of high-expansion polyurethane foam in targeted void spaces offers a compelling and effective retrospective solution for enhancing the damage stability of existing passenger vessels. This innovative approach addresses the shortcomings of traditional methods by providing substantial safety improvements without compromising operational utility, payload capacity, or incurring prohibitive costs. The verified material properties and the successful case study demonstrate the significant potential of this technology to bridge the growing safety gap in the global legacy fleet, contributing to a safer maritime future.

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5. From Coaling Stations to Hydrogen Hubs: Lessons for A Net-Zero Maritime Future

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Abstract: The maritime industry is undergoing an unprecedented and rapid transformation. As the backbone of global trade, the sector now faces the urgent challenge of transitioning to zero-emission vessels in response to mounting environmental pressures and regulatory mandates. A historical analogy, the shift from sail to steam unfolded gradually over the course of a century, shaped by a complex interplay of technological innovation, economic incentives, infrastructure development, military imperatives, and evolving trade demands. In stark contrast, the current transition must occur within a much shorter timeframe, underscored by the International Maritime Organization's (IMO) target of achieving net-zero emissions from international shipping by 2050.

This paper argues that understanding the drivers, constraints, and adaptive strategies of past maritime energy transitions can offer critical insights for managing today's decarbonisation challenges. While technological innovation remains essential, historical evidence suggests that adoption is equally dependent on regulatory frameworks, economic viability, and the availability of supporting infrastructure. The nineteenth-century proliferation of global coaling stations strategically located at ports such as Gibraltar, Aden, and Suez, was underpinned by military and imperial priorities, enabling steamships to displace sail on long-distance routes and reshaping global trade and naval power projection. Simultaneously, the so-called "sailing-ship effect" saw dramatic improvements in sail technology as designers responded to competitive pressure from steam, temporarily extending the commercial viability of wind-powered vessels.

Today, however, the absence of a comparable military or geopolitical imperative leaves the development of alternative fuel infrastructure largely at the mercy of regulatory enforcement and commercial risk appetites. This shift introduces a new layer of vulnerability, without coordinated public investment or strategic urgency, the pace of infrastructure deployment may lag technological readiness, undermining the feasibility of a timely transition. By analysing these historical precedents, this paper identifies key parallels and divergences that can inform contemporary policy and investment strategies. The lessons of the past, particularly the importance of coordinated infrastructure development, targeted policy interventions, and workforce adaptation, are vital for accelerating the adoption of zero-emission fuels and ensuring a just and economically viable transition for the maritime sector.

Keywords: Sail; Maritime Decarbonisation; Energy Transition; Historical Analogy; Policy

1. Introduction

The global maritime industry is a critical artery of global trade. Transporting over 80% of the volume of globally traded goods. Whilst waterborne transport represents the most efficient mode of freight transportation in terms of energy consumption per ton-kilometre, the growing volume of seaborne trade has led to a sharp rise in fossil fuel consumption and associated greenhouse gas (GHG) emissions. As of January 2024, the global merchant fleet comprised approximately 109,000 vessels, with a total carrying capacity of 2.35 billion deadweight tons (dwt). This represents an annual increase of 77 million dwt from the previous year, translating to a fleet capacity growth rate of about 3.4% (UNCTAD, 2024). The sector consumes approximately 330 million tons of marine fuel annually, with 77% being heavy fuel oil (HFO), a low-grade and highly polluting fuel (Hsieh and Felby, 2017). The global merchant fleet is estimated to contribute between 3% and 6% of global carbon dioxide (CO_2) emissions, 14% to 31% of nitrogen oxides (NO_x), and 4% to 9% of sulphur oxides (SO_x), underscoring their significant role in air pollution (Istrate et al., 2022). Projections by the International Maritime Organization (IMO) suggest that, without significant intervention, emissions from marine transport could rise to 15% of global CO_2 emissions by 2050 (IMO, 2020).

In response, the IMO adopted its first legally binding net-zero framework in early 2025, targeting "net-zero" GHG emissions from international shipping by or around 2050 through mandatory emissions limits and industry-wide GHG pricing. The IMO GHG Strategy (2023), sets ambitious climate targets, specifically reducing shipping emissions by at least 40% by 2030 and reaching net-zero emissions by or around 2050 relative to 2008 levels. The strategy introduces indicative checkpoints, including a 20–30% absolute reduction in GHG emissions by 2030 and 70–80% by 2040, and mandates that zero or near-zero emission fuels should comprise at least 5%, striving for 10% of the sector's energy use by 2030 (IMO, 2023a). Collectively, these elements constitute the foundation of the IMO GHG Strategy, delineating a structured and enforceable trajectory for the decarbonisation of international shipping through interim emissions reduction benchmarks, the progressive integration of zero or near-zero emission fuels, and the deployment of market-based regulatory instruments. Strategy further underscores the importance of a just and equitable transition, recognising the imperative for inclusive international collaboration and the provision of targeted support to developing countries. Complementary regional measures, for example, the EU's FuelEU Maritime regulation, applicable from 1st January 2025, mandates progressively stricter reductions in the greenhouse-gas intensity of maritime fuels, further underscoring the urgency of decarbonizing shipping operations (Regulation (EU), 2023). Taken together, these international and regional initiatives reflect a growing consensus on the urgent need for coordinated, multi-level action to align maritime transport with global climate objectives. Meeting these goals will require more than technological innovation; it demands a systemic transformation of the entire maritime sector (Bouman et al., 2017). This includes substantial economic investment in infrastructure and fleet renewal, the development of supportive policy and regulatory frameworks, and sociocultural shifts within maritime institutions and labour forces. Such a transformation must also address the alignment of market incentives with climate objectives, the redistribution of costs and benefits across global supply chains, and the capacity-building needs of developing nations (Ling-Chin et al., 2024).

This current moment of transition echoes a pivotal period in maritime history, namely, the shift from sail to steam in the 19th century. That transformation was not merely technological, it entailed profound changes in ship design, advances in naval architecture, port infrastructure, labour practices, and global trade patterns (Greenhill, 1980). Steamships required new fuel supply chains (notably coal), altered the economics of shipping by enabling more predictable schedules, and gradually displaced traditional sail vessels despite initial resistance from established maritime actors. The transition was uneven, shaped by geopolitical rivalries, colonial interests, the strategic priorities of naval powers, and demonstrated the importance of key historical inflection points (Harley, 2013). Yet the transition was far from smooth, many shipowners resisted steam due to high capital costs and operational uncertainties, echoing contemporary concerns about stranded assets and uneven readiness for decarbonization (Lind et al., 2023). Labour markets underwent significant upheaval, as steamships required new technical skills and roles paralleling today's need for workforce retraining in alternative fuels and digital systems (Kitada et al., 2023; Chin et al., 2006). Concurrently, the shift from sail to steam displaced traditional seafaring roles, triggering resistance among communities with longstanding cultural traditions and historical practices in sail (Manjrekar, 2019; Williams, 1989). Recognising this historical tension is essential to preventing similar challenges during today's technological transitions (Dewan and Godina, 2024).

Maritime history is a narrative of continuous evolution, driven by a constant quest for improved performance, reliability, and efficiency in global trade, transportation, and military dominance. Through reflection on the drivers, barriers, and outcomes of this historical transition, it is possible to draw valuable lessons for navigating today's decarbonisation challenge(s). In particular, the historical case illustrates how technological change deeply intersects with institutional inertia, economic incentives, and geopolitical dynamics. It also underscores the importance of coordinated policy support, investment in enabling infrastructure, and the capacity to manage transitional disruptions, all factors that remain equally relevant in the contemporary push toward zero-emission shipping. This article seeks to explore the historical transition from sail to coal and to draw detailed parallels with the modern shift toward alternative fuels and low emission technologies, such as green hydrogen, ammonia, and advanced marine fuel cells. Through comparison of the advent of the pioneering era of steam with the development of modern alternative fuels and green maritime technologies, this article seeks to uncover recurring themes and challenges that underpin both these maritime energy transitions. The goal was to derive lessons from history that can inform modern policymaking, research agendas, and operational strategies in an industry currently under intense environmental and regulatory scrutiny. This article evaluates these multifaceted dimensions with a focus on both historical legacies and current trajectories.

2. At the mercy of wind and tide: A brief history

The transition from sail to coal-fired steam propulsion in the nineteenth century constitutes a pivotal juncture in maritime history, fundamentally reshaping the technological, economic, and geopolitical landscape of global shipping. For centuries, maritime navigation was constrained by the vagaries of wind and tides, with sailing vessels reliant on seasonal patterns and favourable meteorological conditions. This dependence limited the reliability and efficiency of maritime transport, particularly for long-distance trade and naval operations. The development of steam engines, initially adopted as auxiliary power in the early 1800s and later as the primary mode of propulsion, marked a decisive break from this paradigm, freeing vessels from these natural constraints (John and Williams, 2011). Steamships could operate independently of wind and depart ports at will, overcoming many of the uncertainties that had accompanied maritime travel, facilitating scheduled services and opening new global trade routes. In time the march of technological progress would change all parts of the maritime industry, technology, ship building, finance, port operations and other ancillary maritime services (Pascali, 2017). Parallel advances in the communications - the telegraph, advances in materials – timber and later steel manufacturing, and the expansion of railways, would combined be contribute to an unprecedented increase in international trade and the first wave of trade globalization (1870-1913) (O'Rourke and Williamson, 2001).

Although steamships had emerged as early as the 1810s and 1820s, the transition from sail to steam propulsion in global maritime transport was protracted, taking decades for steam to overtake the proliferation of sail, especially on the longer oceanic routes (Graham, 1956). During this period, sailing technology underwent significant refinement including innovations in copper-sheathed hulls, iron fastenings, and the development of fast clipper ships substantially improved the speed and efficiency of sail-powered vessels (Mendonça, 2013). Consequently, steam propulsion initially gained traction on short-haul, high-frequency routes, such as coastal services and mail lines, where its advantages in reliability and scheduling were most pronounced. On longer oceanic passages, however, sail remained dominant well into the mid-century (Harley, 2013; Smith, 2018). For instance, in 1840, only around 87,000 of Britain's 2.3 million tons of merchant shipping were steam powered. It was not until the 1870s that steam began to decisively displace sail in global trade, and by the early twentieth century, masts had disappeared from most commercial and passenger vessels (Williams, 1989).

The introduction of the screw propeller in the mid-nineteenth century marks one of the most consequential innovations in the history of marine propulsion. Fundamentally reshaping the design, performance, and competitiveness of steam-powered vessels (Lambert, 2003; Carlton, 2018). While the paddle wheel had been instrumental in the early development of steam propulsion, enabling reliable navigation of rivers and coastal waters, it quickly revealed its limitations in open seas. Paddle steamers commonly relied on large, inefficient engines and wood-burning boilers, and their exposed paddle wheels were vulnerable to damage in rough conditions. Moreover, the bulky paddle-boxes constrained hull design and reduced overall efficiency (Robins, 2012; Graham, 1958). In response to these challenges, the 1830s and 1840s witnessed a wave of innovation that culminated in the reinvention of the screw propeller by John Ericsson and Francis Pettit Smith in 1836 (Smith, 2011). Initially met with scepticism, particularly among conservative naval authorities who questioned its practicality and durability, the screw propeller soon demonstrated clear advantages (Lambert, 2017). Unlike the paddle wheel, it was compact, submerged, and less susceptible to damage, allowing for more streamlined hull forms and improved hydrodynamics. Its efficiency in converting engine power into thrust enabled vessels to achieve greater speeds with enhanced fuel economy and maneuverability (Graham, 1958). A series of successful demonstrations quickly overcame institutional resistance, and by the latter half of the nineteenth century, the screw propeller had become the standard in both commercial and naval shipbuilding. Its adoption played a pivotal role in the decline of sail and the modernisation of maritime transport facilitating the expansion of global trade networks and reinforcing the strategic capabilities of steam-powered navies (Lambert, 2017).

Launched in 1843, Isambard Kingdom Brunel's SS Great Britain was the first large steamship constructed with an iron hull, steam boiler and a screw propeller (Lambert, 2003; Carlton, 2018). As engine technology advanced, wooden hulls gave way to iron and later steel, accommodating larger, more powerful machinery (Smith, 2002). The introduction of compound steam engines in the 1860s, and triple-expansion engines by the 1880s (e.g., SS Aberdeen, 1881), dramatically reduced coal consumption, enabling longer voyages (Carlton, 2018); Robins, 2012). Vessels including SS Agamemnon (1865) showcased the efficiency of these new engines (Carlton, 2018). By the late 19th century, further technological breakthroughs such as steam turbines (e.g., Turbinia, 1894) and diesel engines (e.g. HMS Dreadnaught) continued to extend range and performance, further facilitating the global shift from sail to steam (Carlton, 2018; Smith, 2002).

The adoption of coal, and later diesel, as the dominant maritime fuel was closely tied to the industrial revolution and the expansion of global trade (Headrick, 1988; O'Rourke and Williamson, 1999). Coal offered a dense and relatively transportable energy source, and its widespread availability in industrialising nations, particularly Britain, facilitated the rapid proliferation of steam-powered vessels (Robins, 2012; Smith, 2002). The establishment of coaling stations across strategic ports and colonial outposts became essential to sustaining long-distance steam navigation, embedding maritime infrastructure within broader imperial networks (Headrick, 1988; Lambert, 2003). This infrastructural shift not only improved commercial efficiencies but also redefined naval strategy, as access to coal supplies became a critical determinant of maritime power (Graham, 1958; Lambert, 2017). The steamship thus emerged not merely as a technological innovation but as a symbol of industrial modernity and imperial reach, laying the groundwork for the globalisation of trade and the reconfiguration of international economic hierarchies (O'Rourke and Williamson, 1999).

This transformation in maritime logistics had far-reaching consequences beyond the movement of goods. Steam propulsion revolutionised shipping by reducing voyage times and enabling regular, scheduled services. The resulting predictability not only enhanced operational efficiency but also underpinned the expansion of global trade networks, contributing significantly to the first wave of globalisation between 1870 and 1913 (O'Rourke and Williamson, 1999; Rodrigue, 2020). As steamships required substantial capital investment and technical expertise, their adoption accelerated the consolidation of shipping enterprises and fostered the emergence of large, vertically integrated firms (Ville, 1990; Stopford, 2008). This shift also catalysed the professionalisation of maritime services, including marine insurance, ship finance, and port operations, which evolved to support the growing complexity and scale of international shipping (Milne, 2016). In this way, the steam revolution contributed to the restructuring of the maritime economy, embedding it more deeply within the industrial and financial systems of the time (Morrell and Abbenhuis, 2019).

While the transition to steam power brought undeniable economic and logistical benefits, it also introduced new and largely unacknowledged environmental consequences. The widespread adoption of coal as a maritime fuel significantly increased the carbon intensity of global shipping (Fremdling, 1985; Corbett and Winebrake, 2010). Steamships emitted large quantities of soot and sulphur-laden smoke, contributing to air pollution in port cities and along major shipping corridors (Powell, 2022). These emissions not only affected urban air quality but also had deleterious effects on human health and local ecosystems, particularly in densely trafficked colonial ports where coaling operations were concentrated (Headrick, 1988; Powell, 2022). Moreover, the extraction, transportation, and storage of coal imposed substantial environmental burdens. Coal mining led to deforestation, soil erosion, and water contamination, while the global network of coaling stations left a lasting ecological footprint on coastal and island environments (Headrick, 1988; Barak, 2020). Although these impacts were not widely recognized at the time, they foreshadowed the environmental externalities associated with fossil fuel dependence that continue to shape contemporary debates on maritime sustainability and climate change (Rodrigue, 2020; Corbett and Winebrake, 2010).

3. Technological coexistence and the "Sailing Ship Effect"

One of the most instructive insights from the maritime transitions of the nineteenth century is the phenomenon of technological coexistence. The commonly held view that sail and steam were in direct and immediate competition oversimplifies a far more nuanced reality (Harley, 2013; Graham, 1956; Rosenberg, 1972). In practice, the two technologies coexisted for several decades, each occupying distinct commercial and operational niches. Established sailing vessels remained largely unthreatened until the widespread adoption of more efficient triple-expansion steam engines in the early 1880s, which significantly improved the range and fuel economy of steamships (Carlton, 2018). Contrary to linear models of innovation diffusion, the advent of steam propulsion did not render sail immediately obsolete. Instead, sailing ships underwent substantial refinement in response to the competitive pressures introduced by steam. This dynamic is captured in the concept of the "sailing-ship effect", which describes how incumbent technologies may experience a resurgence or accelerated improvement when challenged by emerging alternatives (De Liso et al., 2023; Rosenberg, 1972; Mendonça, 2013). The result was a period of hybrid innovation, in which both sail and steam evolved in parallel, shaped by economic, technological, and infrastructural contingencies (Stafford, 2023; Taylor, 2013).

Complementing and contributing to this period of coexistence was the parallel gradual emergence of science-based naval architecture between 1600 and 1800. This period marked a foundational shift in ship design, aligning with the broader currents of the Scientific Revolution. For the first time, shipbuilders began to apply theoretical principles and mathematical tools to predict a vessel's performance characteristics prior to construction. This transition from artisanal to analytical design laid the groundwork for the more systematic innovations of the nineteenth century, including the optimisation of hull forms, rigging systems, and propulsion technologies (Ferreiro and McGee, 2006). The integration of empirical observation with theoretical modelling not only improved ship performance but also professionalised naval architecture as a discipline, setting the stage for the complex engineering challenges of the steam age (Smith, 2002).

These advances and the competitive stimulus provided by steam propulsion catalysed remarkable innovations in traditional sailing ship design. Economic imperatives, particularly in trades reliant on speed, such as the transport of tea from China or wool from Australia, drove shipbuilders to pursue disruptive innovation. The clipper ships of the 1840s to 1860s exemplify this response, long, narrow-hulled vessels with expansive sail areas, optimized for speed (Taylor, 2013; Knoblock, 2014). Notable examples include the Lightning, which averaged 18.5 knots over a 24-hour period in 1854, and the Flying Cloud, which completed the New York–San Francisco passage in a record 89 days. Between 1837 and the early 1880s, the average sailing time from England to Australia declined from approximately 124 days to 86 (Kentley, 2019). These gains were attributable to a suite of technological and operational enhancements, including copper-sheathed hulls, iron framing, refined hull geometries, and more efficient rigging systems (Knoblock, 2014). Concurrently, advances in meteorological science, particularly the work of Matthew Maury, who encouraged captains to adopt “great circle” routes through the southern oceans, further reducing voyage durations (Smith, 2016).

These developments significantly delayed the dominance of steam on long-haul routes. Even well into the 1880s, windjammers continued to transport bulk cargoes economically on routes where coaling infrastructure remained sparse (Harley, 2013; Graham, 1956). The sailing-ship effect thus underscores the adaptive capacity of incumbent technologies and challenges deterministic narratives of technological succession (De Liso et al., 2023). While steamships offered superior reliability and scheduling, their early deployment was largely confined to short-haul and coastal services (Lambert, 2003). The transition to steam was therefore neither immediate nor uniform, but rather shaped by a complex interplay of route characteristics, cargo types, and infrastructural constraints (Stafford, 2023). Indeed, sail ships continued to be built in large numbers after 1849 when steamships systematically outperformed them, for instance, in 1864, 867 sail ships were built compared to 364 steamships; in 1877, 703 vs. 389; and even in 1892, 322 vs. 521 (Mendonça, 2013; Hatton, 2024).

As a product of technological co-development, the period saw the emergence of hybrid vessels that combined sail and steam propulsion. Many ships were built or retrofitted to operate with both systems, allowing operators to switch between wind and coal power depending on route characteristics, fuel availability, and economic considerations. This flexibility was particularly valuable on long-haul routes where coaling stations were sparse or unreliable. In some cases, vessels were even converted back from steam to sail to reduce operational costs or extend vessel lifespans, especially during economic downturns or in regions where coal was prohibitively expensive (Mendonça, 2013). These hybrid vessels were not merely transitional artefacts but strategic responses to a complex and evolving technological landscape. They exemplify how maritime actors balanced innovation with risk, leveraging the strengths of both propulsion systems to navigate infrastructural, financial, and operational constraints (Stafford, 2023).

A similar pattern, or indeed ‘sailing ship effect’, is evident in the contemporary maritime energy transition. Confronted with regulatory uncertainty, high capital costs, and the uneven global availability of zero-emission fuels, many shipowners are turning to transitional technologies such as liquefied natural gas (LNG), battery-assisted propulsion, and hybrid-electric systems (McCarney, 2020). As of 2024, LNG and battery-hybrid vessels significantly outnumber those equipped for full zero-emission operation, such as those powered by green hydrogen or ammonia, in both the global fleet and the order book (Clarkson’s Research, 2025). This disparity underscores the maritime sector’s current reliance on incremental solutions and highlights the infrastructural and economic challenges facing the adoption of fully decarbonised propulsion systems. These configurations offer partial reductions in greenhouse gas emissions while preserving operational flexibility, closely paralleling the strategic role of sail-steam hybrids in the nineteenth century. For instance, LNG-fuelled vessels can reduce carbon dioxide emissions by up to 20% and virtually eliminate sulphur oxides and particulate matter compared to conventional marine fuels. Hybrid systems, meanwhile, enable optimised fuel use, particularly in port operations and emission control areas where environmental regulations are most stringent (Wang and Wright, 2021).

However, historical analogy also offers a cautionary perspective. Just as hybrid sail-steam vessels extended the viability of sail while infrastructure for steam matured, today’s transitional systems are serving as a bridge toward full decarbonization (De Liso et al., 2023). These technologies are not merely technical stopgaps but strategic responses to a complex and evolving regulatory and technological landscape. The sailing ship effect thus serves, at least in part, as a warning against overly deterministic narratives of technological disruption (Rosenberg, 1972). While improvements in sail technology and hybrid sail-steam vessels extended the operational relevance of sail and allowed time for steam infrastructure and capabilities to mature, they also contributed to delaying the full adoption of the new steam paradigm (Mendonça, 2013; Stafford, 2023). This underscores the importance of viewing technological transitions as contested, path-dependent processes in which multiple systems may coexist, compete, and co-evolve over extended periods (Rosenberg, 1972). A similar challenge and risk exist today. Transitional fuels and hybrid propulsion systems, while offering immediate short-term emissions reductions and operational flexibility, may become entrenched, locking the industry into suboptimal technological pathways and diverting investment away from truly transformative, zero-emission solutions (Bouman et al., 2017; McCarney, 2020). Recognising this dynamic is critical for policymakers, regulators, and industry leaders seeking to accelerate maritime decarbonisation. It highlights the need for a dual strategy, both supporting breakthrough innovations capable of delivering long-term climate goals, while also managing the role of transitional technologies to ensure they serve as bridges rather than barriers to systemic change.

4. Commercial incentives and competition

The transition from sail to steam in the nineteenth century was not driven solely by technological superiority but was fundamentally shaped by commercial logic and economic pragmatism (Harley, 2013; Armstrong and Williams, 2011). While steam propulsion offered clear operational advantages, most notably independence from wind patterns, greater reliability, and the ability to maintain regular schedules, its adoption was uneven and highly contingent on the economic context of specific maritime routes and cargo types. Steamships enabled faster and more predictable voyages, which proved particularly advantageous for time-sensitive cargoes, passenger transport, and government services such as mail delivery (Harcourt, 1988). These attributes aligned well with the growing demands of industrial capitalism, which increasingly prioritised speed, regularity, and logistical precision in global trade networks.

However, the economic calculus of shipowners often favoured continued investment in sail, particularly for long-haul routes involving low-value, high-volume commodities. The high operational costs associated with steam, especially the need for frequent refuelling and the limited global availability of coaling stations, meant that steamships were initially viable only on routes where their advantages could be fully leveraged and where infrastructure supported their operation (Suárez Bosa, 2023). In contrast, sailing vessels, which required no fuel and had lower maintenance costs, remained economically competitive for transporting bulk goods such as grain, wool, and sugar, particularly on routes where voyage duration was less critical to profitability (Graham, 1956).

The commercial viability of steam was enhanced by institutional support mechanisms, particularly government subsidies and mail contracts. The Cunard Line, established in 1840, exemplified this model. Cunard's early success was underpinned by British government subsidies for transatlantic mail service, which provided a stable revenue stream that coal costs and engine maintenance expenses (Harcourt, 1988). These subsidies not only facilitated the expansion of steam services but also created a competitive advantage for firms operating in politically strategic or economically dense corridors, such as the North Atlantic. As a result, steam propulsion initially gained a foothold in high-traffic, high-value routes, where its speed and reliability could command premium freight and passenger rates (Butler, 2004; Williams and Armstrong, 2012).

The opening of the Suez Canal in 1869 marked a pivotal moment in the commercial ascendancy of steam. It cut over 7,000 km from the Europe–Asia maritime route. Due to its narrow and windless design, it rapidly made sailing vessels uncompetitive (Headrick, 1988). Steamships, able to navigate independently of wind, capitalized on this choke point, further reinforcing the strategic and commercial logic of steam investment. The commercial implications were profound. The canal not only reduced transit times but also enabled more frequent and predictable shipping schedules, which were increasingly demanded by industrial economies and colonial administrations. Steamships could now deliver goods, mail, and personnel to and from Asia with unprecedented regularity, reinforcing the economic logic of steam investment. British firms like Cunard and P&O rapidly expanded their East–West operations, consolidating imperial shipping dominance (Williams and Armstrong, 2012). The canal thus served as both a technological enabler and a commercial catalyst, reshaping global maritime logistics in favour of steam. Nevertheless, the broader transition remained uneven. While steam rapidly gained ground on routes where infrastructure and cargo value justified its costs, sailing ships continued to dominate in regions where coaling stations were sparse or where the economics of bulk cargo transport still favoured wind power. By 1870, steamships accounted for only 1.1 million tons of Britain's 5.7 million-ton merchant fleet, a statistic reflecting the continuing economic relevance of sail (Harley, 2013; Graham, 1956).

These dynamics offer valuable insights into the complexities of modern technological change. Much like the steamships that initially thrived in infrastructure-rich, high-value corridors, today's emerging technologies, hydrogen fuel systems and wind-assisted shipping, are gaining traction in contexts where supportive infrastructure (i.e. bunkering), regulatory incentives, and market demand converge. Moreover, the persistence of sail in the face of steam's rise underscores a broader principle: technological transitions are rarely linear or absolute. Incumbent systems often adapt and coexist with emerging alternatives, particularly when they retain economic advantages in specific niches. As sail survived alongside steam, in the contemporary context the internal combustion engine continues to dominate in regions where fuel is cheap and alternative infrastructure is limited (Wang and Wright, 2021).

Government intervention, for commercial derisking and incentivisation, remains a critical factor. Nineteenth-century steamship operators were underwritten by government subsidies, while today's decarbonisation efforts often depend on instruments like carbon pricing, tax incentives, and the implementation of green shipping corridors (IMO, 2020; IMO, 2023a; Regulation (EU), 2023). These mechanisms help bridge the cost gap between established and emerging systems, facilitating gradual market rebalancing rather than abrupt displacement. This reinforces a critical lesson, technological superiority alone does will not ensure rapid adoption. Transitions are path-dependent, shaped by commercial incentives, infrastructure, policy, and risk management in combination (Harley, 2013).

5. Military, and regulatory influences

Naval strategy played a decisive role in accelerating the adoption of steam propulsion. Maritime powers, particularly the British Royal Navy, quickly recognised the tactical advantages conferred by steam-powered vessels. Steam warships could manoeuvre independently of wind conditions, creating an unparalleled degree of operational flexibility. This capability fundamentally altered naval doctrine, enabling fleets to reposition, pursue, or retreat with unprecedented precision (Gray, 2017). The Battle of Navarino (1827), the last major naval engagement fought entirely under sail, marked the end of an era; thereafter, steam power increasingly shaped naval strategy and ship design.

Despite these advantages, the transition to steam met with institutional resistance. The British Admiralty steeped in the traditions of sail warfare were initially sceptical of the new technology. In 1828, the British Admiralty famously warned that steam propulsion was "calculated to strike a fatal blow at the naval supremacy of the Empire," reflecting fears that the Royal Navy's hard-won mastery of sail tactics might be rendered obsolete (Gray, 2017). As a result, early steam-powered vessels were often deployed as auxiliaries rather than frontline warships. It was not until the mid-nineteenth century that the Royal Navy began systematically integrating steam engines and screw propulsion into its fleet, as seen in the retrofitting of HMS Erebus and Terror in 1845 and the launch of HMS Warrior, Britain's first iron-hulled steam-powered battleship, in 1860 (Ferreiro and McGee, 2006).

A critical implication of steam propulsion was its dependence on coal. which fundamentally reconfigured naval logistics and strategy. By the 1870s, the Admiralty recognised that access to global coal supplies would determine naval readiness. In response, the Royal Navy and other maritime powers established global networks of coaling stations. These facilities, located at key outposts including Gibraltar, Malta, Suez, Aden, Trincomalee, and Hong Kong, became essential nodes in both naval logistics and colonial administration (Gray, 2017). The Suez Canal, opened in 1869, became a strategic steam artery: unusable by sail, but ideal for steamships. To ensure its use, Britain deployed bases along the Red Sea and Indian Ocean to protect and supply its steam fleet (Headrick, 1988; Ferreiro and McGee, 2006). This marked a pivotal transformation where state-led military priorities drove infrastructure, innovation, and global influence.

The historical transition from sail to steam was deeply embedded in the geopolitical and military priorities of the nineteenth century: naval strategy, imperial logistics, and the projection of maritime power. The Royal Navy in particular, as a technological patron ensured aligned technological pathways, underwriting, infrastructure development, and standardisation of operational practices. The Royal Navy's global network of coaling stations, for instance, was not only a logistical necessity but also a strategic infrastructure that enabled sustained naval presence and commercial dominance across the British Empire (Gray, 2017). In contrast, the contemporary transition to zero-emission maritime technologies is unfolding in a markedly different international landscape. The decline of military and imperial imperatives has left the maritime sector less influenced by strategic imperatives and more by the dynamics of market forces and regulatory governance (Fadiga et al., 2024).

While the IMO has emerged as the sectors primary regulator, setting emissions caps, energy efficiency standards, and GHG emissions reduction targets, the actual deployment of green infrastructure, (e.g. hydrogen and ammonia bunkering hubs, retrofitting facilities, and green shipping corridors) depends heavily on commercial viability, investor confidence, private-public partnerships. Public–private partnerships have emerged as a key mechanism for coordinating these efforts, but they often lack the strategic coherence and long-term security that characterised state-led initiatives in the steam era (Ash and Scarbrough, 2019). Government and defence-supported research and development programs, including the European Union's Horizon 2020 programme, and the UK's SHORE initiatives echo earlier naval investment by derisking early-stage green technologies (Wang and Wright, 2021).

Nevertheless, the influence of military and strategic imperatives persists. Modern navies maintain global fleets and forward-deployed bases that secure key maritime chokepoints and commercial resilience, particularly in emerging routes like the Arctic (Bhattacharyya et al., 2023). Dual-use infrastructure, such as port upgrades and surveillance systems, often receives defence funding, accelerating developments that also benefit the civilian maritime sector.

Moreover, geopolitical competition, notably among China, the EU, and the United States, is reframing maritime innovation and climate adaptation as a matter of national security and economic sovereignty (Bateman and Bergin, 2020).

This evolving balance from state-driven to market driven innovation introduces both promise and peril. Market competition can accelerate technological development and diversify solutions. However, the absence of a singular unifying strategic body or imperative innovation risks becoming fragmented and uneven. Without the centralised authority once exercised by naval institutions, the burden of coordination now falls on a patchwork of regulatory bodies, industry coalitions, commercial interests, and national governments, with differing priorities and capacities.

In this context, regulatory institutions like those of the IMO must play the role once performed by naval doctrine, much like the strategic imperatives of the steam age they must not only compel technological adaptation for commercial gain but, also maintain compliance and competitiveness in a shifting operational environment. Clear standards, such as the IMO's 2020 sulphur cap and its 2050 net-zero GHG strategy, are shifting capital toward cleaner fuels and vessels (Regulation (EU), 2023; Manjrekar, 2019). These mandates are reshaping investment decisions across the industry, prompting the development of alternative fuels (such as ammonia, methanol, and hydrogen), energy-efficient hull designs, and wind-assisted propulsion systems. Examples such as Höegh E-H_2's ammonia-to-hydrogen terminal and Rotterdam and Singapore's investment in bunkering hubs exemplify how regulation and infrastructure can co-evolve.

Historical precedent therefore suggests that large-scale maritime transformations require more than technological superiority, they demand coordinated infrastructure, systematic investment, and institutional leadership. In the absence of military-driven urgency, the challenge for today's policymakers is to recreate that level of strategic alignment through regulatory foresight, targeted subsidies, and international cooperation. What the Royal Navy achieved with coal and cannons, today's world must achieve with climate policy and green capital. Only then can the maritime sector achieve a transition that is not only technologically feasible but also economically and logistically sustainable.

6. Labour and sociocultural influence

The transition from sail to steam not only reconfigured maritime technology and commerce but also profoundly reshaped the social and occupational structures of seafaring. Steam propulsion introduced new technical demands that gave rise to specialised roles aboard ship. Marine engineers, boilermakers, and stokers became indispensable members of the crew, responsible for maintaining and operating complex machinery below decks. These roles required a distinct set of skills, mechanical aptitude, thermodynamic knowledge, and physical endurance, that diverged sharply from the traditional competencies of sail handling and celestial navigation (Gray, 2017). Working conditions in the engine room were notoriously harsh. Engineers were tasked with monitoring and repairing high-pressure boilers, often in sweltering, poorly ventilated spaces. Stokers laboured continuously to feed coal into furnaces, enduring extreme heat, coal dust, and the constant rhythm of the ship's engines. This shift from open-deck seamanship to enclosed, industrial labour marked a significant cultural transformation in maritime work, moving the locus of skill and authority from the rigging to the engine room (Graham, 1956; Ferreiro and McGee, 2006).

Paradoxically, even sailing ships experienced labour changes during this period. Advances in rigging efficiency, hull design, and auxiliary engine use allowed for smaller crew complements by the late nineteenth century. The romanticised image of the large, wind-driven crew gave way to leaner, more technically oriented teams. The predictability of steam schedules also altered the rhythms of port life. Ships could now arrive and depart on fixed timetables, reshaping the labour dynamics of port-based industries such as coaling, maintenance, and provisioning. Entire communities grew around coaling stations, which became hubs of transient labour and imperial logistics (Headrick, 1988; Shulman, 2015). More broadly, the steam transition mirrored wider patterns of industrialisation ashore, where traditional crafts were increasingly supplanted by mechanised labour. The sea, long a domain of elemental struggle and navigational skill, became a site of industrial discipline and technological specialization (Gray, 2017).

The labour transformations prompted by the steam transition find clear parallels in the contemporary maritime sector, where decarbonisation, automation, and digitalization are reshaping occupational demands. As the rise of steam created new roles, diminishing the centrality of traditional sail-handling skills, the shift toward low-emission technologies and smart shipping systems are creating demand for a new set of competencies while traditional seamanship recedes in prominence (Nazir et al., 2015). Maritime workers are increasingly required to manage digital navigation systems, emissions monitoring technologies, alternative fuels (e.g., LNG, ammonia, hydrogen), and automated engine diagnostics. This evolution necessitates a significant investment in retraining and upskilling. Marine engineers, for instance, must now be proficient not only in mechanical systems but also in software interfaces and environmental compliance protocols. Similarly, deck officers are expected to interpret real-time data from integrated bridge systems and manage increasingly complex logistics chains (Nazir et al., 2015). Institutions like the IMO and national maritime academies are already revising the STCW standards (Standards of Training, Certification and Watchkeeping) to reflect these emerging needs (IMO, 2023b).

The socio-cultural identity of maritime labour is once again in flux. The shift from manual to cognitive labour, reshaping hierarchies, expertise, and the lived experience of life at sea. The modern seafarer inhabits a hybrid environment of part analogue, part digital, just as early steam-era crews navigated both rigging and engines. The rise of autonomous vessel technologies adds a further dimension; operational control may soon move from ship to shore. Remote monitoring, AI-assisted navigation, and shore-based control centres suggest a future in which the seafarer's presence aboard may no longer be a given, but rather a strategic choice (Kitada et al., 2023). This decoupling of labour from the vessel itself represents a profound cultural transformation, with deep implications for training, regulation, and the very identity of maritime work.

7. Conclusions

The transitions in maritime, first from sail to coal, and now from fossil fuels to alternative energy sources, serve as powerful reflections of the broader technological, economic, and sociocultural transformations that have shaped global trade and transportation over the past two centuries. The steam revolution of the nineteenth century redefined maritime operations by improving speed, reliability, and strategic reach. Yet it also demanded substantial capital outlay, widespread infrastructure development, and a profound reorganisation of maritime labour. Today's shift toward low-emission technologies and alternative fuels echoes many of these patterns, though intensified by the existential challenge of climate change and the requirement for clear regulatory structures to address it.

At the core of both transitions lies sustained technological innovation. The nineteenth-century shift was not the product of a single invention but a convergence of breakthroughs: steam propulsion, screw propellers, iron and steel hulls, and the rise of scientific naval architecture. Similarly, the modern decarbonisation effort is driven by developments in green fuels such as hydrogen and ammonia, as well as advancements in vessel design, energy systems, and digital technologies. In each case, successful adoption depends not only on technological readiness but also on long-term research and development capable of addressing technical, infrastructural, and operational challenges.

Infrastructure and economics play equally central roles. Just as the global spread of coaling stations enabled the steamship to displace sail, today's energy transition hinges on large-scale investment in bunkering hubs, storage facilities, and vessel retrofits. The financial barrier remains high: alternative fuels are more expensive than conventional marine fuels, and fuel costs continue to comprise the majority of operational expenditure for shipowners. Economic viability remains, as it did in the past, a determining factor in shaping adoption trajectories.

State power and strategic imperatives were critical accelerators of steam technology. Naval priorities and imperial logistics underwrote infrastructure development and supported early adoption through military procurement and planning. While modern transitions lack the overt imperial drive of the nineteenth century, strategic imperatives have not disappeared. Dual-use infrastructure, defence funding, and geopolitical competition are once again aligning national security with commercial innovation. However, in contrast to the centralised authority of naval institutions, today's governance landscape is fragmented. The coordination of transition efforts now rests with a complex network of regulatory bodies, industry coalitions, and national governments, each pursuing overlapping but not always aligned objectives.

Environmental regulation, particularly through international frameworks such as those of the International Maritime Organization (IMO), have become the dominant force shaping the direction and pace of maritime innovation. Emissions targets, fuel standards, and state-backed innovation programs now steer industry decisions, integrating sustainability imperatives into commercial and technical planning. These regulatory mechanisms serve not only to constrain emissions but also to enable investment by providing stability and long-term orientation.

Labour and cultural change remain fundamental to the success of any technological shift. The age of steam redefined maritime work, creating new professions and shifting the centre of skill from deck to engine room. Today, maritime labour is once again transforming, with demands for digital fluency, environmental compliance, and expertise in alternative fuels. As automation and remote technologies emerge, the very identity of the seafarer is being reimagined. Ongoing investment in training, trust-building, and inclusive workforce adaptation is vital to ensure a just and effective transition.

Viewed historically, the parallels between past and present are striking. Both the historical shift from sail to steam and the contemporary move toward alternative fuels have involved significant technological leaps, high initial costs, and the need for extensive infrastructural (re)development. Each has required not only technical innovation but also sociocultural adaptation and workforce transformation. Yet there are also clear divergences, particularly in the role of regulation. While the age of steam was marked by minimal oversight, the modern transition is defined by notably different structures of global governance and accelerating pressures of environmental constraints. These similarities and contrasts offer valuable lessons. As the maritime sector charts a course toward a net-zero future, historical insight is not merely informative, it is indispensable. Ensuring that this transformation is economically viable, socially inclusive, and environmentally responsible will require not only innovation, but coordination, leadership, and a clear-eyed understanding of the past.

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6. Comprehensive Analytical Investigation of Microporous Layer (MPL) Structural Modifications: Advancing Proton Exchange Membrane Fuel Cells (PEMFCs) Performance Optimization and Durability

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Abstract

The current study provides a rigorous analytical study of the characteristic changes of the microporous layers in PEMFCs for changing and enhancing their efficiency and life expectancy. This work strictly investigates numerous electrochemical factors influencing the MPL architecture to perform the investigations on the influence of structural improvements on the properties of the MPL such as porosity or hydrophpatibility and electrical conductivity using state-of-art X-ray imaging and real-experiment comparison. Evidenced priorities highlight the centrality of updating MPL design for flood prevention, better reactant distribution and superior cell performance in various operational environments without exception with an emphasis on such advanced concepts as gradient porosity and surface modification for the highest PEMFC performance. In addition, this work offers prescriptive knowledge into the specificities of MPL modification for future industrial uses, identifying issues that define the feasibility and applicability of MPL modifications for industrial use. Therefore, this work successfully synthesises the major material science knowledge with real engineering foundation and sets the benchmark for further development of PEMFC technology in the global efforts to develop sustainable and highly efficiency energy systems as well as identifying innovative solutions to improve energy conversion efficiency and lifespan of next generation PEMFCs.

Keywords: PEMFCs technology; MPL modification; Hydrophpatibility; X-ray imaging; Energy systems

1. Introduction

Proton-exchange membrane fuel cells (PEMFCs) serve as essential components for sustainable energy technologies because they demonstrate highly efficient operation and environmental benefits and flexible use for transportation and stationary power systems. The electricity generation capability together with low environmental effects of PEMFCs positions them as an outstanding replacement for conventional fossil fuel-powered systems (Müller-Hülstede et al., 2025; Smith et al., 2025; Tamilarasan et al., 2024). The commercial transformation along with mass implementation of PEMFCs encounter critical difficulties due to their operating boundaries and production expenses and service lifetime problems. The solution of these problems demands extensive knowledge about cell components combined with innovative material and design advancements.

PEMFCs contain essential components where the microporous layer (MPL) stands out as a fundamental performance enhancer. The MPL which exists between GDL and CL functions as a multifunctional element to distribute reactants uniformly and manage water effectively while decreasing contact resistance. Properties of microporous layer structure and materials influence both how well MPL functions and how efficiently PEMFC operates and maintains its operational lifespan. Design optimization of the MPL stands as the essential factor for PEMFC technology advancement (Cheng et al., 2024; Xia et al., 2024; Yakubu et al., 2024).

The existing MPL designs prove insufficient for resolving major PEMFC challenges including water flooding together with poor mass transport and mechanical degradation. Operation problems caused by these issues lead to both cell performance deterioration and shortened operational readiness (Hao et al., 2023; Hua et al., 2024; Xiong et al., 2025). Experimental studies demonstrate that MPL structure enhancement through the modification of pores and surface and material composition leads to substantial reduction of PEMFC operational obstacles. The insufficient analytical framework for evaluating these structural modifications needs to be developed because present research demonstrates this necessity. Advanced analytical methods together with simulation tools give researchers new capabilities to analyze MPL internal processes alongside its interactions with PEMFC components. Researchers use blending SEM with XRD and CFD in their investigations to evaluate nanoscale and microscale structural transformations (Chen et al., 2022; Wang et al., 2024; Xu et al., 2024). Experimental approaches alongside computational methods allow precise optimization of MPL designs that resolve significant performance-limiting aspects of PEMFC devices and their lifespans.

The research investigates the structural alterations made to MPLs to improve PEMFC operating characteristics and product lifetime stability. The research targets pivotal factors which define MPL performance by introducing new design solutions through experimental and simulation evaluation. The research analyses structural modifications to evaluate their effects on performance metrics to create a universal framework for optimal MPL design. The results of this analysis can completely transform PEMFC production through upgraded methods which solve persistent performance strength and durability issues (Alrwashdeh et al., 2018; Alrwashdeh et al., 2017a; Alrwashdeh et al., 2017c). General structural modifications of the MPL present opportunities to solve water management problems and enhance thermal stability and mechanical strength for PEMFCs which will permit broader PEMFC applications. The research outcomes can assist scientists in developing improved future fuel cell technologies alongside their contribution to worldwide clean energy solution development (Naouar et al., 2024; Sultana et al., 2024; Wang et al., 2025; Yang et al., 2024).

The research fulfils its purpose by conducting an extensive performance analysis of MPL modifications on PEMFC operation. The initial part of this work examines past literature that details MPL designs together with their encountered challenges. Study presents experimental and computational methodologies then shows an evaluation of resulting data significance. The study ends by offering future research path recommendations and practical implementation strategies for advancing PEMFC technology through optimized MPL designs.

2. Modelling

PEMFC modelling of MPL structural modifications needs an analytical system which unites electrochemical evaluation with transport analysis and mechanical properties. The main goal involves developing mathematical expressions to define how MPL properties relating to porosity and wettability and electrical conductivity affect PEMFC operational performances (Alrwashdeh et al., 2022; Alrwashdeh et al., 2018; Alrwashdeh et al., 2017a; Alrwashdeh et al., 2017b).

The governing equations for reactant and water transport within the MPL are derived from the conservation laws. The mass transport of species follows the generalized diffusion equation (Cai et al., 2024; Chen et al., 2022; Chen et al., 2025; Cheng et al., 2024; Derakhshannia and Moosapour, 2024; Duan and Kang, 2024):

$$\frac{\partial C_i}{\partial t} + \nabla . (D_i \nabla C_i) = R_i$$

where:

- C_i is the concentration of species i,
- D_i is the effective diffusivity,
- R_i represents the reaction rate term associated with electrochemical consumption.

The permeability of the MPL to gaseous species is influenced by its porosity ε and tortuosity τ, which can be described using the Bruggeman correlation (Haddad et al., 2024; Hai et al., 2024; Hao et al., 2023; Hua et al., 2024; Jamil et al., 2016; Jing et al., 2024):

$$D_{eff} = D_o \frac{\varepsilon}{\tau}$$

where:

- σ is the surface tension,
- θ is the contact angle defining hydrophobicity,
- k is the permeability of the MPL.

Optimizing the surface structure of the MPL through gradient porosity or tailored wettability improves water evacuation efficiency, preventing flooding while ensuring optimal membrane hydration (Cai et al., 2024; Chen et al., 2022; Chen et al., 2025; Cheng et al., 2024)**.**

The electrical conductivity of the MPL, which influences contact resistance and current distribution, is modelled using the effective medium theory (Luo et al., 2023; Müller-Hülstede et al., 2025; Naouar et al., 2024; Raga et al., 2024; Rezk and Faraji, 2024):

$$\sigma_{eff} = \sigma_o \frac{\varepsilon}{\tau}$$

where σ_0 represents the bulk conductivity of the material. Similarly, thermal conductivity is modelled using a composite rule based on the structural composition of the MPL:

$$K_{eff} = K_{solid}(1 - \epsilon) + K_{gas}\epsilon$$

where k_{solid} and k_{gas} denote the thermal conductivities of the solid and gas phases, respectively. The optimization of MPL microstructure significantly affects the thermal stability and energy dissipation characteristics of PEMFCs. The modelling system provides fundamental knowledge needed to develop improved next-generation MPLs which better handle water and distribute reactants and increase durability leading to more efficient PEMFC operation.

3. Results and discussion

The assessment of microporous layer (MPL) structural modifications in PEMFCs reveals important performance-related information about reactant spread, water handling, electrical conductance and the life duration of cells. The research utilizes experimental methods with numerical tools to analyze how different MPL characteristics influence fuel cell behavior across different operating conditions. High-resolution X-ray tomography alongside electrochemical impedance spectroscopy (EIS) and polarization curve analysis measures performance changes that result from MPL modifications through an in-depth examination of microstructural properties. The investigation devoted its main attention to understanding how gradient porosity structures and surface modifications affect mass transport phenomena inside the MPL. The conventional uniform design of membrane-electrode interfaces encounters multiple drawbacks in processing reactants while managing excess fluid which causes degradation due to either reactant insufficient supply or fluid buildup. Engineered pore sizes that match specific hydrophobic properties serve to enhance the membrane's capillary-driven water removal process while stopping flooding from excessive liquid while maintaining optimal membrane water levels. Main sustenance of high proton conductivity depends on maintaining this perfect balance which also minimizes performance losses from excessive ohmic resistance. Structural improvements lead to diminished interfacial contact resistance because through-plane and in-plane electrical conductivity tests confirm this fact.

The conducted analysis demonstrated how modified MPL formulations successfully improve the mechanical properties and operational endurance of the fuel cell design. Standard MPL materials demonstrate good reactant diffusion capability but need improvement in durability because they break down mechanically during multi-operational cycles and especially under dynamic loads. A PEMFC system operating lifespan becomes longer because modified MPLs feature novel composite materials with reinforced carbon structures that deliver superior mechanical strength. Experimental research aligned with computational modelling proves the theoretical advantages of these designs by showing procedural and spatial uniformity improvement in current flow and reactant access throughout the system. The subsequent parts of this work show comprehensive quantitative performance enhancements through detailed breakouts between original and redesigned MPL systems. The evaluation of power density enhancements together with reduced activation and ohmic losses as well as improved thermal stability leads to a comprehensive foundation for future MPL design techniques. The study utilizes various methods to validate MPL enhancements as PEMFC palliatives before establishing guidelines for future high-performance fuel cell infrastructure.

The impact of MPL modifications on PEMFCs undergoes thorough study through Figure 1. The evaluation centers on power density and ohmic resistance in combination with water content since these measurements determine fuel cell operational efficiency and stability factor. Energy output from power density measures per area unit with current density as the x-axis variable according to the blue scale on the first y-axis. The graph compares Modified MPL (blue circles) and Baseline MPL (cyan squares). The modified MPL design shows better power output performance than the baseline under all current densities according to the analysis. Modified system performs better due to better reactant distribution capabilities and optimized water handling which both minimize mass transport effects and enhance chemical reaction efficiency. The red secondary axis shows ohmic resistance measurements according to current density values. The red diamond markers in the Modified MPL resistivity plot display lower values compared to the pink triangle markers in the Baseline MPL resistivity graph. Optimized pores and material structure create better pathways for electron transport and lower the contact resistance between GDL and CL layers. Ohmic resistance reduction through improved fuel cell efficiency occurs because less energy is lost during the process of electron conduction. Water content within the cell device is measured through the tertiary y-axis presentation system (green). The Modified MPL uses green crosses to illustrate its better ability to manage water in a stable manner above the baseline MPL which uses olive plus signs.

Optimal water management requirements exist in PEMFC systems because they help prevent flooding but also support sufficient membrane liquid saturation. The baseline regime demonstrates unstable water retention patterns leading to performance degradations yet the modified water transport method in the modified MPL maintains better cell stability. These performance results confirm that modifications made to MPL are fundamental to increasing PEMFC performance values. When modified with improved characteristics relating to porosity distribution and electrical conductivity along with hydrophobicity the modified MPL can deliver enhanced power output while reducing energy losses and achieving superior operational lifetime. Presented research aims to form basis for developing advanced MPL designs that will enable highly efficient and commercially usable PEMFC technology.

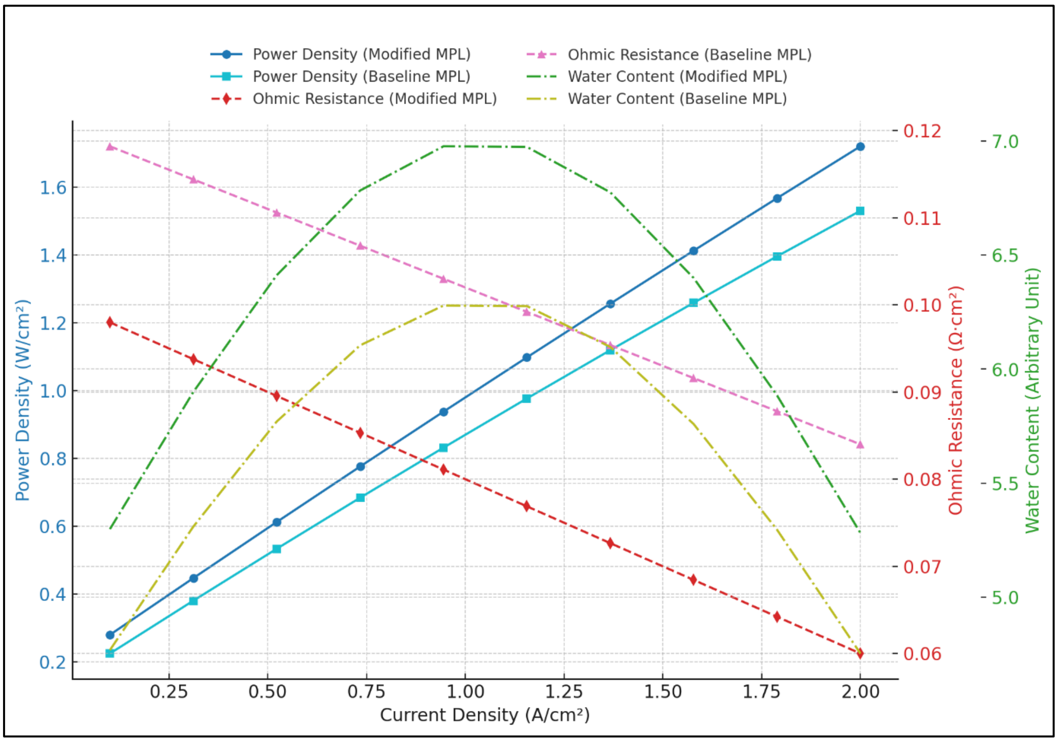

Figure 1. The impact of MPL modifications on the performance of PEMFCs. It highlights three key performance parameters—power density, ohmic resistance, and water content

Figure 2 displays a thorough examination of performance changes in PEMFCs regarding their efficiency and pressure drop and thermal stability while varying MPL modifications during operating temperature conditions. PEMFC technology depends on these three parameters as significant indicators which measure its operational viability and optimization achievement. The research data demonstrates that MPL structural modifications produce concrete impacts on fuel cell electrochemistry along with reactant transport performance and operational lifespan. Energy conversion efficiency stands as a top performance factor in fuel cell technology because it shows the extent to which the system converts chemical energy into electrical power. The analysis shows the modified MPL (blue circles) demonstrates superior efficiency levels than the baseline MPL (cyan squares) through every measured temperature level. Low temperatures between 50–60°C reduce the efficiency of both MPL designs because slow electrochemical reactions along with enhanced activation losses occur. The operating temperature increase improves efficiency measurements for both designs since higher temperatures accelerate reaction kinetics. As the main finding this research demonstrates that the advanced MPL design preserves better efficiency results than the original design throughout all testing conditions.

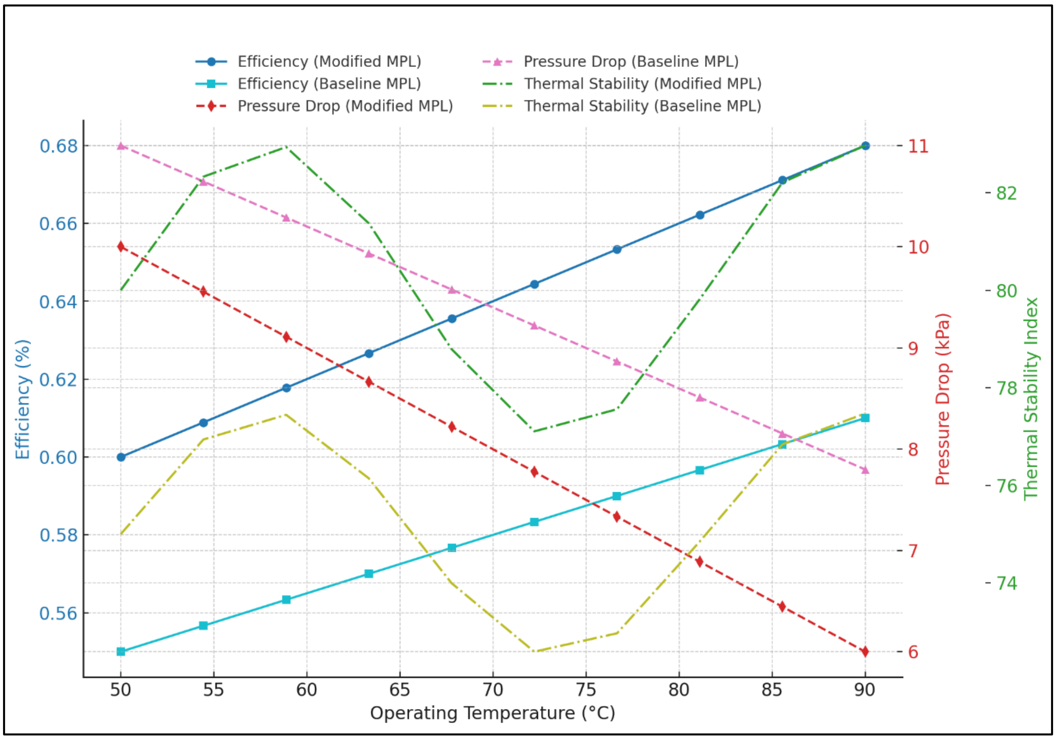

Figure 2 Impact of MPL modifications on PEMFC performance across different operating temperatures.

The MPL achieves enhanced efficiency because of various modifications which include: The new MPL structure improves reactant gas transmission while it redistributes pores so both limitation factors and reaction uniformity improve. The improved water management through hydrophobic surface treatment prevents flooding thus becoming a significant performance loss factor in traditional PEMFC designs. The change in MPL material composition leads to better electrical conductivity which reduces resistive losses to enhance efficiency. The efficiency of the modified MPL grows to 66% at operating temperatures reaching 85°C although the baseline shows an efficiency below 62%. The structure changes to the MPL demonstrate their ability to enhance PEMFC electrochemical reactions while improving power output.

The essential performance parameter for PEMFCs includes pressure drop that mediates gas flow resistance in fuel cell structures. High pressure drop defines restricted reactant transport that causes increased system losses and elevates additional energy requirements for compressors or blowers. Lakeland TX Study revealed that the modified MPL creates better pressure drop trends (red and pink lines). The red diamond-shaped pressure drops results from the modified MPL display reduced pressure loss and enhanced maintenance of stability when contrasted against the baseline MPL pressure drop trends (pink triangles) at all assessed temperatures. Multiple concurrent factors result in a decrease of pressure drop across the system: Through structural changes in the modified MPL mold the optimized pore network produces paths with less gas transport resistance. By creating a structure with better permeability, the catalyst layer receives reactants more swiftly which improves the overall performance of the fuel cell. The MPL experience better water management as floods in the MPL block gas routes which causes pressure increase. After hydrophobic treatment the modified MPL builds a barrier which stops water accumulation in gas channels. The modified MPL structure maintains pressure drops lower than 9 kPa in contrast to baseline MPL pressure which reaches above 10 kPa at standard temperatures. The structural modifications to the MPL become more evident at elevated temperatures which confirms that these enhancements lead to decreased operational burden resulting in enhanced efficiency together with durability.

Fuel cell reliability depends strongly on their thermal stability as well as several additional fundamental influences. The fuel cell operation develops inconsistencies and materials degrade, and mechanical stress rises when temperature fluctuates. Thermal stability trends (green and olive lines) confirm that the modified MPL (marked green crosses) holds superior thermal response characteristics in addition to showing better stability than regular MPL (presented as olive plus signs). The ability of a fuel cell to dissipate heat while keeping temperature distributions consistent indicates its thermal stability. The stability index shows oscillatory patterns when various thermal effects take place among the membrane system and its catalyst layer and reactant gases. The modified MPL achieves a sustained stability index throughout all temperature conditions thus demonstrating that its new design enhances heat distribution along with structural integrity.

Several advancements contribute to better thermal stability through these reasons: Enhanced thermal distribution throughout the fuel cell is possible because the modified MPL consists of materials showing increased thermal conductivity. The structure of the cell shows enhanced resistance against thermal cycling because repeated heat and cooling stresses do not easily damage materials. The modified MPL keeps its durability intact while dealing with environmental effects which ultimately improves total cell service time. The cell requires proper humidity control because membrane conductivity depends on it. Through water retention regulation the modified MPL safeguards fuel cells against membrane drying and takes away risk of excessive condensation. Affording better fuel cell lifespan are these upgrades that perform optimally in systems with changing operating temperatures and power requirements.

These data show that MPL optimization stands as a crucial requirement for PEMFC technology advancements. The modified MPL design successfully resolves major PEMFC challenges including reactant distribution alongside water management and thermal stability improvements because of its effective enhancement abilities. The research lays an important basis for industrial adoption and experimental verification that will create sturdy and efficient PEMFC systems for future use. The research findings serve to develop future PEMFCs which will increase efficiency while reducing operational expenses and increasing service duration for fuel cells to achieve true sustainability in energy applications.

The voltage losses and efficiency trends in a PEMFC operate as a function of increasing current density through analytic Figure 3. The parameters must be fully understood to optimize PEMFC design mainly when designing MPL modifications which enhance both operational efficiency and durability of the system. The electrochemical performance of a fuel cell depends greatly on three main voltage loss components which include activation loss and ohmic loss and concentration loss which appear in the provided graph. The secondary parameter within the graph demonstrates the efficiency changes that result from these energy conversion losses. The activation loss reaches its peak level at lower current densities based on the blue curve representation. The energy barrier which electrochemical catalyst reactions need to surpass yields this loss popularity. The oxygen reduction reaction at cathodes slows down significantly in PEMFC applications thus creating high activation losses. The reaction speed hikes up together with enhanced catalyst efficiency which results in activation loss reduction when current density elevates.

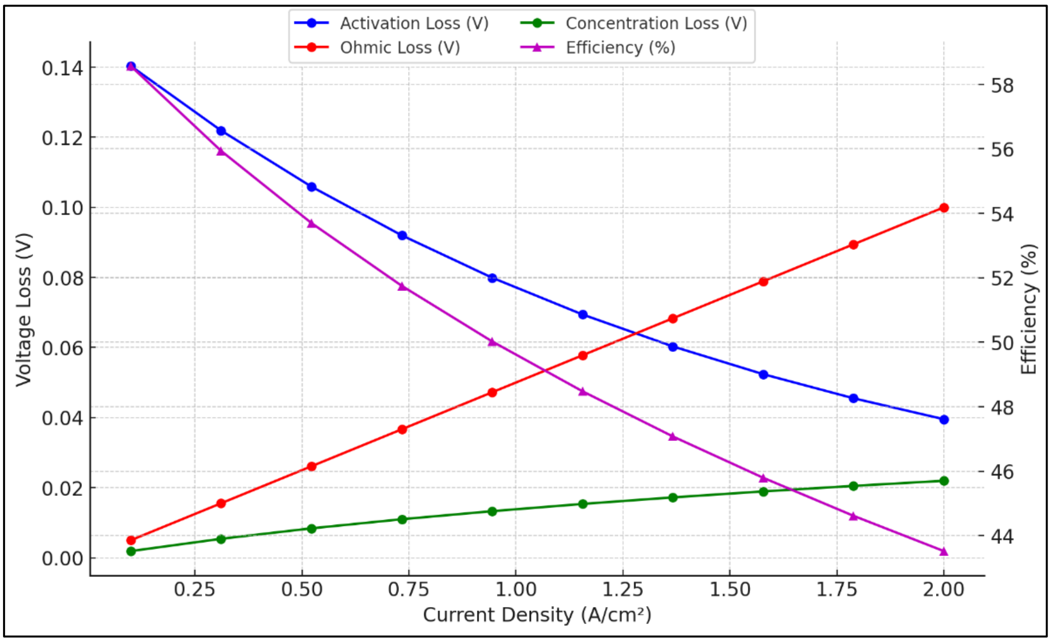

Figure 3 The breakdown of voltage losses in a PEMFC with increasing current density, alongside efficiency variations

The fundamental need exists to tackle activation losses by enhancing catalyst optimization together with improvements in microporous layers to maximize reactant distribution and lessen losses at lower current densities. The rising current density causes Ohmic loss to shift linearly according to the red curve. The main source of loss in the cell components stems from resistance found in the proton-conducting membrane together with both the gas diffusion layers (GDLs) and MPL. The proton conductivity level inside membranes plays a crucial role in determining overall cell performance because all proton transportation resistance lowers the cell voltage output. The electrical resistance in electrode and bipolar plate connections with the cell contributes to substantial loss. adjustments or conductive additive incorporation within the MPL structure reduces ohmic resistance while building more effective transportation channels for electrons and ions which consequently enhances cell efficiency.

The green curve depicts concentration loss that emerges when current densities become elevated because of reacting material diffusion constraints. The inefficient diffusion of reactants especially oxygen at the cathode occurs because water accumulation combined with inadequate gas flow causes transport issues. The requirement for reactants rises with greater current density which creates depleted areas inside the electrode layers. At high current densities water production reaches excessive levels that fill the pores inside the MPL and GDL thus blocking reactant transport.

The performance of PEFC under high power output conditions becomes more stable with reactive substance diffusion enhancements achieved through gradient porosity MPL designs combined with hydrophobic coatings that manage water distribution. The PEMFC operates versus current density according to the expressed efficiency data on the purple curve. Voltage losses create a direct correlation with the logarithmic decrease of efficiency. The efficiency stays at a high level when operations occur at lower current density levels due to limited losses that preserve optimal working parameters. An increase in current density leads to efficiency reduction because it creates negative effects from activation losses and concentration losses and ohmic losses. The design and material developments implemented into the MPL work to fight off these adverse effects through they promote reaction distribution while improving the electrical and thermal properties and enabling optimal water handling.

The data in the graph demonstrates the crucial importance of performing improvements on the microporous layer to maximize PEMFC efficiency and operational sustainability. Fuel cell efficiency benefits substantially when MPL modifications enhance catalyst distribution for activation loss reduction and achieve better electrical conductivity to decrease ohmic loss and implement pore structures for concentration loss management.

The potential strategies developed using advanced material engineering approaches combine hydrophilic-hydrophobic gradient insertion with conductive carbon insertions and optimized pore size distribution optimization to address the graph's demonstrated challenges. The comprehensive voltage loss examination together with efficiency trends analysis demonstrates how multiple electrochemical and transport phenomena function in PEMFCs. The analyzed graph demonstrates that MPL modifications executed through systematic strategies enable the reduction of performance-limiting losses which results in improved operational efficiency. Future research and engineering work must focus on perfecting both structural designs and material characteristics of MPL because this will ensure fuel cell performance quality needed for automotive and portable power sustainability.

Figure 4 shows the complete relationship between operating temperature variations on key PEMFC performance indicators including power density together with membrane water content measurement and voltage efficiency. Fundamental knowledge of these relationships remains crucial during fuel cell design particularly regarding the modification of microporous layers to achieve better durability and efficiency. The findings expose sophisticated relationships among temperature together with electrochemical reaction speeds and water content in PEMFC membranes because these elements are vitally important for PEMFC operations. Charcoal blue indicates the density of power as the operating temperature changes. Power density rises exponentially with increasing temperature according to the examined trend. Temperature increases the rate of electrochemical reactions resulting in enhanced charge transport between catalysts with better performance outcomes. Temperatures higher than room level decrease activation losses and let the cell output increased amounts of power. While this was a positive improvement, operating cells at extremely high temperatures leads to multiple negative effects that shortens their operational lifespan. The combination of MPL modifications with external cooling mechanisms should be used to achieve both sufficient power output optimization and material stability maintenance.

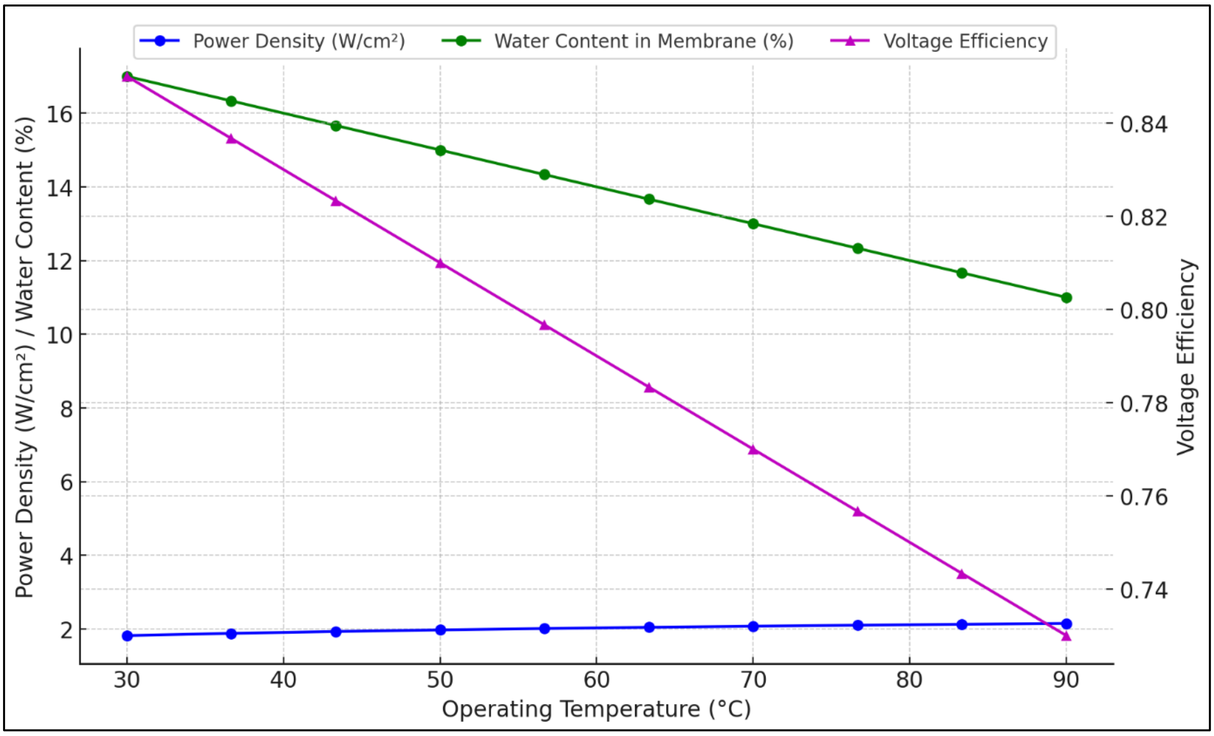

Figure 4 The influence of operating temperature on key performance metrics of a PEMFC

The green line depicts how operating temperature affects water content in the membrane through an inverse correlation. The membrane retains less water as operating temperature rises along a linear scale. The higher temperature increases water evaporation speed thus leading to membrane dehydration. Proton conducting capacity in PEMFCs is directly linked to membrane hydration levels thus membrane dryness negatively affects ionic transport performance. A severe state of dehydration leads to higher ohmic resistance and membrane thinning which results in mechanical failure. Various combination of gradient porosity MPLs and improved gas diffusion layer (GDL) hydrophobicity and external humidification techniques enable maintenance of optimal hydration levels throughout different temperature ranges. Voltage efficiency data shows a continuous yet small degradation trend as the temperature rises during the experimental period. Rising temperatures benefit PEM fuel cell reactions since they boost power production, but very high temperatures increase resistance losses and diminish raw material concentration. Temperature increases result in membrane thinning effects in addition to increasing gas crossover rates that eventually reduce PEMFC operational efficiency. Proper thermal management measures should exist to maintain long-term stability and efficiency because operating PEMFCs at higher temperatures might initially improve performance but could lead to performance decline over time. Water retention control and MPL improvements at different temperatures help extend the operational stability of PEMFC voltage performance.

The presented graph demonstrates why it is crucial to optimize the microporous layer (MPL) for proper water regulation along with thermal stability and mass transfer in PEMFCs. A properly constructed microporous layer (MPL) protects membranes from dehydration by uniting hydrophilic and hydrophobic elements which ensure sufficient water retention at elevated temperatures. Advanced materials used for MPL design help dissipate excessive heat through their improved thermal conductivity properties which creates localized heat dissipation that prevents efficiency loss. The system stability and PEMFC reliability improve due to these modifications which operate effectively under different conditions. The analysis demonstrates why PEMFC operation depends heavily on proper thermal control systems. The advantages of rising temperatures in reaction speed and power output generation exist alongside unwanted effects that include membrane water loss and reduced operational efficiency. The combination of advanced MPL structures with proper humidification protocols along with external Cooling solutions enables mitigation of PEMFC operational challenges. Upcoming MPL research needs to create subsequent designs which unite temperature-enduring materials together with autoregulating hydration control to sustain efficient PEMFC operations.

The research concludes that structural rearrangements of microporous layers in PEMFCs produce important effects on system operation and longevity performance. The performance improvements became more evident when MPL parameters were optimized for pore distribution as well as materials selection and surface modifications. Through these merged advances PEMFC systems operate with better distribution of reactants and enhanced electrochemical performance and improved water management systems which counteract operational hurdles that constrained PEMFC durability. Advanced MPL designs demonstrate exceptional robustness to operating conditions since they maintain performance stability despite different operational conditions. These modifications demonstrate potential for commercial PEMFC implementation due to their reduction of pressure drops and their creation of better gas diffusion channels which prioritize efficiency and reliability.

4. Conclusion

The research presents an extensive studying that analyses how modified MPL structures affect PEMFCs performance efficiency and durability. Experiments together with computational models and practical demonstrations show how designs of better MPLs address important operational difficulties. The research investigated three modifications consisting of gradient porosity distribution together with hydrophobic surface treatments and optimized material composition that resulted in enhanced fuel cell efficiency and reactant transport and thermal stability performance. The study confirms how MPL engineering plays a critical part in improving fuel cell technology for industrial-scale deployment. The main outcome of this study demonstrates how modified MPL structures achieve superior reactant distribution while optimizing mass transport performance. The optimized pore structures and design configuration of new MPL enhance uniform reactant gas diffusion which enables maximum efficiency of the catalyst layer. The modified PEMFC performance improves power density and total energy conversion efficiency which makes these cells more practical for high-power applications including automobiles and aerospace sectors and stationary power projects. The optimized MPL structure delivers lowered pressure drop which proves this modification increases energy efficiency together with cost effectiveness in PEMFC operation.

The study assesses the influence of altered MPL structure on water control mechanisms for flood prevention. Traditional PEMFC technology has an important operational restriction due to its sensitivity to water accumulation that degrades performance in electrode layers. Despite operating conditions, the modified MPL system incorporates hydrophobic coatings and structured pores which reduces water accumulation to maintain hydrated operating conditions free from flooding conditions. The discovery brings vital advancements that improve PEMFC dependability and operation lifespans especially under humid and changeable load conditions which present significant water management obstacles. This research shows conclusively that modifications made to the MPL structure enhance the thermal performance and structural stability of the fuel cell. The modified MPL engineering enables fuel cells to work efficiently across various temperatures thus minimizing the formation of hotspots and preventing membrane drying and thermal degradation. The research results show that modified MPL structures optimize performance stability throughout extended operating periods making PEMFCs more suitable for long-term sustainable energy management systems.

The research findings contribute fundamental knowledge about how to manufacture and scale up MPL modifications. Analysis of proposed design improvements verified their implementation feasibility through methods which maintain economic productivity during manufacturing processes. The research establishes necessary foundations for massive implementation of enhanced MPL structures which will power upcoming PEMFCs. Additional research efforts should concentrate on improving structural modifications through advanced manufacturing methods which incorporate nanomaterials in order to optimize PEMFC performance alongside cost-effectiveness. Beyond PEMFCs the research significance reaches broader electrochemical energy systems and advanced material engineering because of its methodologies and findings. The optimization methods researched in this work demonstrate possible applications for other electrochemical operations such as redox flow batteries and supercapacitors and water electrolysis systems which together advance global efforts in renewable yet efficient energy systems. The next-generation fuel cell components can be developed through future research which combines multi-scale modelling with real-time diagnostics and experimental validation for superior performance alongside economic viability and durability.

The research shows that carefully designed MPL modifications create an effective way to deal with main performance limitations in PEMFC technology. The research presents revolutionary PEMFC optimization by handling key issues of reactant distribution and water management and thermal stability and system efficiency. This work has enabled critical discoveries which simultaneously drive forward fuel cell engineering advancement while creating base principles for future sustainable energy technology innovations. The findings generated in this study will direct the development of upgraded PEMFC systems which will be deployed in real-world applications because of expanding international demand for energy solutions that are ecological and efficient and easily sized.

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7. Risk-Based Fire Safety Design Framework for Modern Cruise Vessels: An Integrated Approach to Enhanced Maritime Safety

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Abstract: Fire safety aboard cruise ships represents one of the most significant safety challenges within the maritime sector. The operational context of these vessels—isolated at sea, accommodating thousands of passengers and crew, integrating complex systems within constrained spaces, and offering limited evacuation options—results in a unique and elevated risk profile. Addressing this complexity requires a shift from conventional prescriptive approaches to more adaptive, risk-based approaches. This paper proposes a comprehensive framework for the application of risk-based fire safety design on cruise ships. It critically examines the limitations of traditional prescriptive (rule-based) approaches, which may restrict design flexibility and fail to account for the specific operational and architectural characteristics of modern cruise vessels. By contrast, the risk-based approach allows for tailored safety solutions that align with a vessel's unique features while ensuring regulatory compliance and maintaining high levels of safety. The study analyses common fire hazards encountered on cruise ships, including ignition sources, combustible materials, and system vulnerabilities. It then introduces advanced mitigation strategies encompassing fire prevention, detection, containment, and evacuation planning. The proposed framework also facilitates the integration of innovative technologies and design concepts, enabling the development of safer and more efficient cruise ships. The findings underscore the importance of adopting risk-based (performance-based) design philosophies to address emerging risks and support continuous improvement in maritime fire safety.

Keywords: Risk-based fire safety design; Cruise ships; Fire prevention strategies; Fire mitigation strategies; Regulatory compliance

1. Introduction

Fire accidents aboard modern cruise ships (see Figure 1) represent one of the most critical safety challenges in contemporary maritime operations. Unlike land-based structures, ships present distinctive difficulties during fire emergencies: they operate in isolated marine environments, offer limited escape routes, and contain confined internal spaces that can accelerate the spread of fire. Moreover, they rely exclusively on onboard firefighting systems, with no immediate access to external emergency assistance. The consequences of such incidents can be severe, potentially compromising the structural integrity of the vessel and endangering the lives of thousands of passengers and crew members.

Historically, maritime fire safety has been governed by prescriptive regulatory frameworks, most notably through the International Maritime Organization's (IMO) Safety of Life at Sea (SOLAS) Convention. These regulations establish detailed requirements for fire detection, prevention, and suppression systems. While such standards have contributed significantly to improvements in onboard fire safety, they are often perceived as inflexible and may not adequately address the complexities introduced by contemporary vessel designs and evolving operational practices. Furthermore, prescriptive approaches do not necessarily facilitate the optimal allocation or integration of fire safety resources.

In response to these limitations, the risk-based design (RBD) approach has emerged as a more adaptive and holistic methodology for enhancing fire safety at sea. Rather than focusing solely on compliance with predetermined regulatory criteria, RBD encourages ship designers and operators to systematically identify, assess, and mitigate specific fire risks based on the vessel's unique design characteristics and operational profile. This approach promotes the development of tailored safety solutions that allow for greater flexibility and innovation, while maintaining—or exceeding—established safety standards.

This paper proposes a framework for the implementation of risk-based fire safety design in cruise ships. It examines common causes of onboard fire accidents, analyses lessons learned from historical events, outlines methodological approaches for fire risk assessment, explores design considerations particular to cruise vessels, and presents advanced strategies for risk mitigation. Ultimately, the objective is to contribute to the ongoing evolution of maritime fire safety, shifting from a prescriptive, one-size-fits-all model towards a performance-based paradigm that more effectively safeguards human life, vessel integrity, and the marine environment (Xie, 2001; IMO, 2001; Spyrou et al., 2020).

Figure 1. Icon of the Seas, The World's Largest Modern Cruise Ship (Adapted from: Agency Riviera Maya, 2025).

2. Primary sources of fire on board cruise ships

Fire hazards aboard cruise ships arise from a variety of sources, each characterized by distinct risk profiles that require systematic consideration within a comprehensive safety design framework. A thorough understanding of these sources is essential for the development of effective risk-based strategies for fire safety (Luo and Shin, 2019).

2.1. Engine room fires

According to Koromila and Spyrou (2019), the engine room is the most common point of origin for shipboard fires, as evidenced by maritime accident statistics. Such incidents typically stem from a combination of interrelated factors, including:

1. Fuel or lubricant leaks coming into contact with hot surfaces
2. Overheating of propulsion machinery components
3. Electrical malfunctions within power generation systems
4. Inadequate maintenance of mechanical equipment

Fires in the engine room are particularly hazardous due to the concentration of flammable materials and the critical role of these systems in the vessel's propulsion and electrical operations. On 7 September 2015, while docked at the Port of Charlotte Amalie in St. Thomas, U.S. Virgin Islands, the Carnival Liberty experienced a fire in its engine room (see Figure 2, below). The fire originated in the ship's aft engine room and was attributed to a leak in a fuel supply line, which sprayed fuel onto a hot surface, igniting a blaze. The crew activated the ship's fire suppression systems, and the fire was extinguished without injuries to passengers or crew. However, the incident resulted in the cancellation of the remainder of the cruise. The National Transportation Safety Board (NTSB) investigation highlighted the importance of regular maintenance and inspection of fuel lines and components to prevent such occurrences (NTSB, 2017). This incident underscores the critical nature of engine room fires and the necessity for stringent maintenance protocols and rapid emergency response measures to ensure the safety of passengers and crew.

Figure 2. The fire aboard the Carnival Liberty caused by loose bolts in the engine room (The Maritime Executive, 2017).

2.2. Electrical system failures

Modern cruise ships are equipped with extensive and complex electrical systems that support a wide range of functions, from navigational equipment to passenger amenities. Faulty electrical wiring, as identified by Koromila and Spyrou (2019), is a major fire risk across all vessel types. Electrical fires may arise from various causes, including:

1. Short circuits in ageing wiring systems
2. Overloaded electrical circuits
3. Substandard installation practices or inadequate repairs
4. Water ingress into electrical components
5. Failure of protective electrical devices

Given the widespread distribution of electrical infrastructure throughout a cruise vessel, such failures can initiate fires in virtually any onboard location. On 25 June 2024, Seatrade Cruise News (2024) reported that a fire broke out aboard the Icon of the Seas, the world's largest cruise ship operated by Royal Caribbean International (see Figure 1, above), while docked at Costa Maya, Mexico. The minor blaze occurred in a crew area and was attributed to an electrical fault. Although the fire caused a temporary loss of power, it was swiftly extinguished, and no injuries were reported. The ship continued its scheduled itinerary without further incident.

2.3. Galley and food service areas

Galleys constitute one of the most concentrated fire risk zones on cruise ships due to the continuous, high-volume cooking operations required to serve thousands of meals each day. Galley fires, as noted by Rhine (2024), are frequently caused by the following factors:

1. Unattended cooking activities, particularly during peak meal preparation periods
2. The accumulation of grease in exhaust hoods, ventilation ducts, and on cooking surfaces, which may ignite when exposed to elevated temperatures
3. Malfunctioning or poorly maintained kitchen appliances such as ovens, deep fryers, and other high-temperature cooking equipment

The combination of sustained heat sources, flammable cooking oils, and continuous use renders galley areas particularly vulnerable to onboard fire outbreaks. A notable example of a fire incident originating in a galley occurred aboard the Costa Diadema (shown in Figure 3, below) on 14 August 2024. In the early hours of the morning, a fire ignited in the main galley while the vessel was enroute to Stavanger, Norway. The ship's automated fire suppression system, along with the prompt response of the crew, successfully contained and extinguished the blaze, resulting in no injuries or significant damage. The incident did not disrupt the cruise schedule, allowing passengers to continue their journey with minimal interruption. This event underscores the critical importance of stringent safety measures and the effectiveness of crew emergency training in managing fire risks within food service areas of cruise ships.

Figure 3. Costa Diadema is a Dream-class cruise ship owned by Carnival Corporation and operated by Costa Crociere. (Source: CruiseMapper, 2024)

2.4. Accommodation areas

Passenger and crew accommodation areas present distinct fire risks due to:

1. Electrical appliances in cabins (hair dryers, curling irons, personal electronic devices)
2. Smoking materials improperly discarded
3. Combustible furnishings and decorative materials
4. Unauthorized use of heating devices or open flames

The high occupancy of these areas increases both the probability of human error leading to fire ignition and the potential consequences of fire events. The fire aboard the Star Princess on 23 March 2006 serves as a notable example of a fire accident originating within the accommodation spaces of a modern cruise ship. As shown in Figure 4, the vessel suffered extensive damage after a blaze erupted on a passenger balcony—most likely due to a discarded cigarette igniting combustible materials. According to the UK Marine Accident Investigation Branch (MAIB), the fire spread rapidly across adjacent balconies and cabins, fueled by flammable elements such as polycarbonate partitions, polyurethane deck tiles, and plastic furniture. The absence of fire detection and suppression systems in these external areas, combined with a lack of structural and thermal barriers between fire zones and decks, significantly contributed to the fire's escalation. The incident resulted in one fatality due to smoke inhalation, injuries to several passengers and crew, and damage to nearly 300 cabins. This case illustrates the heightened fire risk within accommodation areas of cruise ships when combustible materials and insufficient fire safety measures are present (MAIB, 2006).

Figure 4. Fire onboard the Star Princess cruise ship, showing flames extending across multiple decks. (Source: USA Today, 2016)

2.5. Technical and service spaces

Specialized areas aboard cruise ships, such as laundry facilities, waste management zones, and technical workshops, house equipment and materials that pose unique fire hazards. These hazards typically arise from:

1. Overheating of laundry equipment
2. Spontaneous combustion of improperly stored linens
3. Presence of flammable materials in maintenance areas
4. Heat-producing repair operations, such as welding or grinding

These areas require particular attention due to the combination of high-temperature equipment, flammable substances, and ongoing technical operations, which significantly increase the risk of fire. On 20 July 1998, shortly after departing the Port of Miami en route to Key West, Florida, the Carnival Ecstasy experienced a fire that originated in its main laundry room (see Figure 5, below). The fire spread through the ventilation system to the aft mooring deck, igniting mooring lines and causing the vessel to lose power and drift. The U.S. Coast Guard responded with six tugboats to assist in firefighting and towing operations. The fire was brought under control by onboard firefighters and extinguished by approximately 9:09 PM. Fourteen crew members and eight passengers sustained minor injuries, and one passenger required extended hospitalization due to a pre-existing condition. The incident resulted in damages exceeding $17 million (NTSB, 2001).

This incident underscores the importance of regular maintenance and safety protocols in specialized areas such as laundry facilities, where equipment and materials can pose unique fire hazards.

Figure 5. The aftermath of the fire aboard the Carnival Ecstasy (Walker, 2013)

2.6. Influence of ship layout and operations

The architectural configuration and operational dynamics of modern cruise ships play a critical role in shaping their fire risk landscape. Several design and operational factors can worsen this vulnerability:

1. The vertical arrangement of compartments across multiple decks can facilitate the upward spread of fire and smoke through stairwells, lift shafts, and service trunks.
2. Expansive open-plan areas, such as atriums, theatres, and entertainment venues, can enable rapid fire propagation and present challenges to effective compartmentation.
3. High passenger occupancy levels increase the complexity of emergency evacuation and crowd management.
4. Continuous 24-hour operations result in sustained equipment use without downtime, heightening the risk of system failures.
5. The diversity of onboard activities—including food preparation, recreational events, and technical maintenance—creates heterogeneous fire risk profiles across different zones of the vessel.

Recognizing the interplay between ship design, onboard operations, and fire hazards is essential to the development of comprehensive, risk-informed fire safety strategies tailored to the unique characteristics of cruise ships.

Cruise ships must be divided into Main Vertical Zones (MVZ) which should not be longer than 48 m, and not larger in area than 1600 m^2on any deck; see Figure 6. These zones are insulated from each other with an A-60 bulkhead, called MVZ bulkhead, or main fire bulkhead. These size limits are today exceeded on most of the large new cruise ships, enabled by “Alternative Design”.

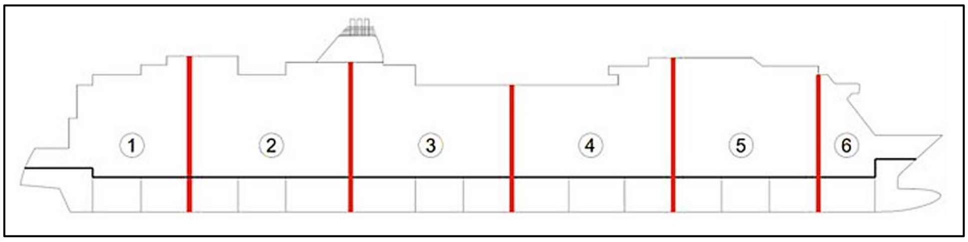

Figure 6. Main Vertical Zones (MVZ) (Aarnio, 2023)

3. Historical frequency analysis

Understanding the historical patterns of fire incidents on cruise ships provides critical context for risk-based design approaches. While comprehensive statistical data is limited in the provided search results, significant insights can be extracted from available information.

3.1. Incident frequency and trends

According to Vassalos and Fan (2016), a database comprising 577 fire incidents (including near-misses) over 111 ship-years was used to develop numerical models for fire occurrence. This equates to approximately 5.2 incidents per ship-year, underscoring the persistent nature of fire hazards in maritime operations. Although the dataset is not exclusive to cruise ships, it provides a valuable baseline for understanding fire frequency in commercial maritime contexts.

Komianos (2023) indicates that cruise ships account for the highest frequency of fire accidents among passenger vessel types, although RoPax (roll-on/roll-off passenger) vessels report higher fatality rates. This disparity may be attributed to several operational factors, including:

1. The increasing size and complexity of modern cruise vessels
2. Continuous day-and-night operations
3. Greater variety of onboard facilities and services
4. Larger numbers of passengers and crew members

Furthermore, Komianos (2023) observes that despite notable advancements in fire safety regulations and technologies, the overall frequency of fire incidents has remained relatively stable across the analysed data. This trend suggests that while large-scale fires may have become less common, core ignition risks continue to persist in maritime operations.

3.2. Fire origin distribution

Koromila and Spyrou (2019) indicate that, based on broader maritime statistics, engine rooms are the primary location for fire ignition on vessels, accounting for approximately 60% of all shipboard fires. Other significant areas where fires commonly originate include:

1. Galleys and food preparation areas
2. Electrical distribution panels and equipment rooms
3. Accommodation spaces
4. Technical workshops and maintenance areas

This distribution of fire origins is critical in shaping risk-based design approaches, helping to identify priority areas that require enhanced fire protection measures.

3.3. Fire incident severity classification

Vassalos and Fan (2016) indicate that fire incidents can be classified according to their severity and outcomes into:

1. Near-misses: Incipient fires detected and extinguished before significant damage occurs
2. Minor incidents: Fires contained within the space of origin with minimal disruption to operations
3. Significant events: Fires extending beyond the space of origin, requiring substantial firefighting effort
4. Major casualties: Extensive fire spread resulting in significant damage, potential injuries, or fatalities
5. Total loss incidents: Catastrophic fires leading to abandonment and/or complete loss of the vessel

3.4. Risk factors influencing incident outcomes

Historical analysis identifies several key factors that influence whether an ignition event escalates into a serious casualty (Bal Beşikçi & Tavacıoğlu, 2017; Wang et al., 2023; MoviTHERM, 2024):

1. Detection time – Early fire detection greatly improves the likelihood of successful containment and mitigation.
2. Crew response effectiveness – Outcomes depend heavily on the crew's training and the prompt, effective execution of emergency procedures.
3. Fire containment – The performance of structural fire protection measures and compartmentation plays a critical role in limiting fire spread.
4. Fire suppression system performance – The reliability and suitability of both fixed and portable firefighting systems directly impact the fire's progression.
5. Ventilation control – Effective management of airflow to the affected area is essential in reducing fire intensity and preventing escalation.

Understanding these historical patterns provides essential context for the development of risk-based design strategies. The persistent frequency of fire incidents, despite significant regulatory advancements, underscores the need for innovative, performance-based approaches to maritime fire safety—approaches that target specific risk factors rather than relying solely on prescriptive compliance.

4. Risk identification and assessment

Risk-based fire safety design begins with the systematic identification and evaluation of fire hazards unique to cruise vessel operations. This process integrates both qualitative and quantitative methods to construct a comprehensive understanding of potential fire scenarios, including their likelihood and potential consequences.

4.1. Methodological framework

The methodological framework for risk-based fire safety design on cruise ships involves a structured sequence of activities aimed at identifying, analyzing, and mitigating fire risks (Koromila & Spyrou, 2019; Pawling et al., 2012; Wang et al., 2023; Bal Beşikçi & Tavacıoğlu, 2017; Komianos, 2023). The process typically includes:

1. Hazard Identification – Systematic review of shipboard systems and operations to determine potential ignition sources and vulnerable areas, using tools such as Hazard and Operability Studies (HAZOP) or checklists derived from historical incident databases.
2. Risk Analysis – Analysis of the frequency and potential consequences of the identified hazards using qualitative tools (e.g., risk matrices) and quantitative methods such as Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Monte Carlo simulations, and consequence modelling tools.

3. Risk Estimation – Quantitative assessment of individual fire hazards by combining the estimated frequency of occurrence with the severity of potential consequences. This step produces numerical risk values that support the prioritization of hazards and guide the allocation of safety resources. In engineering terms, risk is typically expressed as:
$$Risk = Frequency \times Consequence$$
4. Risk Evaluation – Comparison of estimated risks against established risk acceptance criteria to determine their acceptability or the need for mitigation measures.
5. Risk Mitigation Strategies – Selection and implementation of appropriate risk control options, including technical solutions (e.g., improved suppression systems), operational procedures, and crew training enhancements.
6. Documentation and Communication – Recording assumptions, data sources, and results to support transparency and facilitate communication with stakeholders, including regulatory authorities.
7. Review and Iteration – Continuous monitoring and periodic re-evaluation to ensure ongoing effectiveness and adaptation to changes in vessel design, operations, or regulatory requirements.

4.2. Human factors in risk assessment

Gundić et al. (2021) emphasize that human factors significantly influence both the likelihood of fire ignition and the severity of its consequences aboard cruise ships. Key considerations include:

1. Occupancy patterns, which affect the probability of ignition and complicate evacuation dynamics.
2. Crew response capabilities, which directly influence the containment and outcome of fire incidents.
3. Passenger behavior during emergencies, which impacts evacuation efficiency and overall safety.
4. Maintenance practices, which determine the reliability and operational readiness of fire safety systems.

A comprehensive fire risk assessment must incorporate these human-related variables alongside technical and structural aspects to provide an accurate understanding of fire dynamics in the cruise ship environment.

4.3. Quantitative risk criteria

Risk-based design requires establishing acceptable risk criteria, which is essential for determining the effectiveness of safety measures. Risk assessment for cruise vessels usually involves evaluating two key types of risk:

1. Individual risk: The likelihood of fatality for a single person onboard.
2. Societal risk: The potential for multiple fatalities in a single event.

To compare the evaluated risks against established risk acceptance criteria, F-N curves (frequency versus number of fatalities) can be used, as referenced by Vassalos and Fan (2016). These curves provide a graphical representation of societal risk, helping to determine whether the assessed risks fall within acceptable limits. By integrating these risk assessment approaches, effective resource allocation can be made, prioritizing fire safety measures based on the most significant hazards specific to cruise ship operations.

5. Risk-based fire safety design principles

Risk-based fire safety design (RBFSD) marks a significant departure from conventional prescriptive approaches in maritime safety engineering. Instead of solely following predefined regulations, RBFSD adopts a performance-driven methodology that focuses on addressing specific risk factors identified through comprehensive and systematic analysis. This approach aims to optimize fire safety measures based on actual risk scenarios rather than theoretical standards. The following section delves into the core principles and practical applications of risk-based fire safety design, specifically tailored for cruise ships.

5.1. Conceptual framework

Risk-based fire safety design (RBFSD) fundamentally diverges from traditional prescriptive approaches in several critical ways:

1. Goal-oriented vs. specification-oriented: RBFSD emphasizes achieving broader safety objectives, focusing on actual outcomes rather than merely fulfilling specific technical requirements.
2. Holistic system perspective: RBFSD adopts a comprehensive view, addressing the interactions between various systems, spaces, and human factors, rather than considering individual components in isolation.
3. Quantitative risk evaluation: RBFSD employs probabilistic methods and consequence analyses tools to assess risk levels, providing a data-driven approach to evaluate the effectiveness of safety measures.
4. Design flexibility: By prioritizing performance over strict adherence to prescriptive rules, RBFSD encourages innovative solutions tailored to the unique characteristics of each vessel.

As Vassalos and Fan (2016) highlight, the risk-based approach allows for the integration of multiple hazards, such as fire and flooding, within a unified framework, thereby enabling a more comprehensive and effective safety assessment.

5.2. Regulatory framework

The implementation of risk-based fire safety design (RBFSD) is underpinned by several key regulatory frameworks and methodological tools:

1. SOLAS Chapter II-2, Regulation 17 – This regulation permits the use of "Alternative design and arrangements", allowing ship designs to deviate from traditional prescriptive requirements if they can demonstrate, through engineering analysis and justification, an equivalent or superior level of safety.
2. MSC/Circ. 1002 – This circular offers comprehensive guidelines for the approval process of alternative and equivalent fire safety measures, ensuring that proposed solutions are rigorously assessed for compliance with safety standards.
3. Fire Safety Index – Inspired by the Subdivision Index used in damage stability evaluations, the Fire Safety Index serves as a quantitative measure of both passive and active fire protection performance, facilitating the comparison of different design options within a unified framework (Vassalos & Fan, 2016).

These provisions support the practical application of risk-based design principles, fostering innovation while ensuring that safety standards are not only maintained but potentially enhanced.

5.3. Design elements specific to cruise ships

Risk-based fire safety design (RBFSD) enables cruise ship designers to move beyond prescriptive requirements and implement tailored safety measures that align with identified risks. The following design elements illustrate how RBFSD principles can be applied across key domains:

A. Space planning and compartmentation

Risk-based fire safety design allows for adaptive compartmentation strategies that reflect actual fire risk rather than rigid geometric standards:

1. Optimized Main Vertical Zone (MVZ) configuration – MVZ sizing and layout may be determined through risk analysis, focusing on minimizing fire spread and optimizing evacuation, rather than relying solely on prescriptive dimensional criteria.
2. Risk-informed structural fire protection – The application of A-class and B-class divisions can be guided by fire risk profiles of specific spaces, enabling a more efficient allocation of structural fire protection resources.
3. Strategic placement of high-risk spaces – Locating galleys, technical rooms, and other ignition-prone areas in zones that limit potential consequences enhances fire containment and protection.
4. Implementation of fire breaks in open areas – As discussed by Vassalos and Fan (2016), fire breaks between segmented superstructures are effective in restricting fire spread across large, open deck areas.

B. Detection and alarm systems

Detection systems can be tailored through a risk-based approach to enhance early warning capabilities:

1. Risk-based detector density – Areas identified as high-risk may be equipped with denser detector coverage, supported by fire modelling rather than uniform grid spacing.
2. Multi-criteria detection technologies – Deploying a range of detectors (e.g., smoke, heat, flame) based on expected fire signatures improves detection accuracy across different compartments.
3. Intelligent alarm management systems – Alarms can be prioritized and displayed according to the severity and location of the risk, improving situational awareness and response coordination.

C. Suppression systems

Suppression systems can be optimized for specific risks, improving their efficiency and cost-effectiveness:

1. Performance-based water mist systems – Tailoring suppression system specifications to individual space characteristics allows better protection compared to generic system design.
2. Targeted selection of suppression agents – Fire suppression media (e.g., CO_2, foam, water mist) should be chosen based on the characteristics of potential fires in each space.
3. Redundancy in critical areas – Additional or overlapping suppression systems may be justified in locations identified as having elevated risk profiles.

D. Evacuation design

Evacuation strategies under RBFSD leverage modelling and analysis to ensure timely and safe evacuation:

1. Evacuation modelling and simulation – Dynamic simulation of passenger and crew movement during fire scenarios supports optimal layout of escape routes and egress points.
2. Risk-informed arrangement of lifeboats and muster stations – The spatial distribution of evacuation equipment and muster areas is based on the analysis of fire scenarios and their potential impact zones.
3. Smoke management systems – Active (e.g., mechanical extraction) and passive (e.g., smoke barriers) systems are designed using Computational Fluid Dynamics (CFD) fire and smoke modelling tools to address predicted smoke movement and maintain tenable conditions.

E. Material selection

Fire safety performance of materials is evaluated beyond regulatory compliance through advanced testing and risk assessment:

1. Performance-based fire testing – Materials are assessed based on real fire exposure conditions, considering ignition, heat release, and flame spread characteristics.

2. Risk-weighted material distribution – More stringent fire performance requirements may be applied to areas with higher fire risk or consequences of failure.
3. Use of novel materials with protective measures – As Evegren (2010) highlights, even materials with inherent combustibility, such as Fiber Reinforced Polymers (FRP), may be safely used when paired with appropriate insulation and fireproofing strategies.

5.4. Implementation process

The successful application of risk-based fire safety design (RBFSD) in cruise ship development requires a structured, evidence-driven process. This approach ensures that fire safety measures are appropriately aligned with the vessel's unique risk profile. The key steps involved in implementation are:

1. Hazard Identification: A comprehensive and systematic process to identify all potential fire hazards associated with the ship's design, function, and operational profile.
2. Risk Analysis: Quantitative analysis of each identified hazard by evaluating the likelihood (frequency) of occurrence and the severity of its potential consequences.
3. Risk Evaluation: Comparison of estimated risk levels against defined acceptance criteria, such as individual and societal risk thresholds, to determine whether the design meets safety expectations.
4. Design Development: Formulation of integrated safety solutions—including detection, suppression, compartmentation, and evacuation systems—specifically targeted to mitigate the most critical risks.
5. Verification and Validation: Demonstration that the proposed design meets performance-based safety objectives through a combination of analytical modelling, physical testing, and, where applicable, independent third-party assessment.
6. Documentation: Preparation of a comprehensive safety case, including design rationale, risk analyses, verification results, and compliance justifications, to support regulatory approval and operational reference.

RBFSD offers a performance-driven alternative to conventional prescriptive approaches. By prioritizing interventions based on risk significance, RBFSD not only enhances design flexibility but also has the potential to yield superior fire safety outcomes. As Vassalos and Fan (2016) note, cruise ships designed under risk-based frameworks have exhibited improved resilience and safety performance compared to their prescriptively designed counterparts.

6. Risk Mitigation and prevention strategies

Effective risk mitigation and prevention strategies represent the practical implementation of risk-based design principles. These strategies must address the specific fire hazards identified through risk assessment while optimizing resource allocation based on risk significance. This section outlines advanced approaches to fire risk reduction on cruise ships.

6.1. Passive fire protection strategies

Passive fire protection forms the foundational layer of defence against fire spread and provides critical time for evacuation and firefighting operations.

A. Advanced compartmentation approaches

- Risk-based structural fire protection: Tailoring insulation requirements based on fire risk analysis rather than uniform application of A-class, B-class standards. This may include:
    1. Enhanced protection for high-risk boundaries
    2. Optimized protection for low-risk boundaries
    3. Special attention to penetrations and boundary interfaces
- Innovative fire stopping: Implementation of specialized fire barriers in critical locations:
    1. Fire breaks between superstructure sections (Vassalos & Fan, 2016)
    2. Deployable fire curtains for large openings
    3. Intumescent seals for cable and duct penetrations
- Safe application of novel materials: Composites such as FRP may be used safely with layered thermal insulation ensuring up to 60 minutes of fire resistance, as demonstrated by Evegren (2010).

B. Material selection and lifecycle management

- Performance-based material testing and selection: Moving beyond standard classification testing to evaluate actual fire performance in realistic scenarios.
- Risk-weighted furnishing criteria: Tighter controls apply in areas with high risk or critical functions.
- Ongoing integrity management: Passive fire protection systems are maintained through regular inspections and lifecycle assessments.

6.2. Active fire protection systems

Active systems detect, contain, and suppress fires, with their design optimized through risk-based approaches.

A. Advanced compartmentation approaches

- Multi-sensor detection networks: Integration of different detector types (smoke, heat, flame, gas) to improve reliability and reduce false alarms.
- AI-assisted detection systems: Implementation of machine learning algorithms to:
    1. Recognize fire signatures more accurately
    2. Differentiate between normal operations and hazardous conditions
    3. Predict potential fire development based on early indicators

- Risk-based detector distribution: Optimizing detector placement and density according to:
    1. Probability of fire ignition in each space
    2. Potential fire growth rates
    3. Criticality of protected areas

B. Innovative suppression approaches

- Targeted fixed systems: Selection of suppression agents based on specific protected hazards:
    1. High-pressure water mist for machinery spaces and accommodation areas
    2. Clean agents for electrical equipment spaces
    3. Foam systems for hydrocarbon fire risks
- Smart suppression activation: Integration of detection and suppression systems with decision support capabilities to:
    1. Confirm fire presence before discharge
    2. Target suppression to specific fire locations
    3. Adjust suppression parameters based on fire characteristics
- Redundant protection for critical areas: Implementation of multiple, diverse suppression systems in highest-risk locations.

6.3. Operational and human factors

Recognizing that human performance influences safety outcomes, RBD integrates operational preparedness.

A. Crew training and response

- Scenario-based training: Exercises reflect vessel-specific fire risks and simulate realistic emergency responses.
- Decision support tools:
    1. Real-time evacuation routing
    2. Fire progression visualization
    3. Response coordination interfaces
- Drill diversity: Fire drills encompass non-standard, high-consequence scenarios identified through risk modelling.

B. Maintenance and inspection protocols

- Risk-based maintenance scheduling: Prioritizing maintenance activities based on
- Continuous monitoring of critical systems: Implementation of remote sensing and condition monitoring for key fire safety systems.

- Proactive replacement programs: Scheduled renewal of components before reliability degradation rather than upon failure.

6.4. Regulatory framework integration

The implementation of risk-based fire safety measures must occur within existing regulatory frameworks while pursuing appropriate approvals for alternative designs.

A. SOLAS compliance approaches

- Equivalent safety demonstrations: Documentation of how alternative designs provide equivalent or superior safety compared to prescriptive requirements.
- Performance-based compliance: Demonstration of meeting functional requirements and safety objectives rather than specific technical provisions.
- Approval of alternatives: Following established processes for approval of innovative solutions:
    1. SOLAS Chapter II-2, Regulation 17 procedures
    2. MSC/Circ. 1002 guidelines for alternative designs

B. Integration with safety management systems

- Documentation of risk controls: Clear identification of risk mitigation measures in vessel safety management systems.
- Operational limitations: Establishment of any necessary operational constraints associated with alternative designs.
- Continuous improvement processes: Regular review and updating of risk assessments and mitigation strategies based on operational experience.

6.5. Preventive measures for specific fire hazards

Preventive strategies should be developed to address the most common fire sources aboard cruise ships:

A. Engine room fire prevention

- Leak detection systems: Early identification of fuel and lubricant leaks before they contact hot surfaces.
- Surface temperature monitoring: Continuous monitoring of potentially hot surfaces in proximity to combustible materials.
- Predictive maintenance: Use of vibration analysis, oil analysis, and other techniques to identify potential equipment failures before they create fire hazards.

B. Electrical fire prevention

- Advanced circuit protection: Implementation of arc fault detection and smart circuit protection.
- Thermal imaging monitoring: Regular inspection of electrical systems to identify potential hot spots.

- Cable management systems: Improved routing and protection of electrical cables to prevent damage and degradation.

C. Galley fire prevention

- Enhanced ventilation and filtration: Improved systems to prevent grease accumulation in exhaust ducts.
- Automatic cooking monitoring: Implementation of technologies to prevent unattended cooking situations (Rhine, 2024).
- Regular cleaning protocols: Scheduled cleaning of cooking surfaces, hoods, and ducts to prevent grease buildup (Rhine, 2024).

The integration of these advanced risk mitigation and prevention strategies represents a comprehensive approach to fire safety that moves beyond compliance to optimization. By directing resources toward the most significant risks, risk-based fire safety design can achieve higher levels of protection while potentially reducing unnecessary costs associated with uniform application of prescriptive requirements.

7. Conclusion and recommendations

Risk-based fire safety design represents a paradigm shift in the protection of cruise ships, their passengers, and crew from the persistent threat of fire. This research has explored the foundations, methodologies, and practical implementation of risk-based approaches within the context of cruise ship operations, highlighting their potential to significantly enhance safety outcomes while allowing for greater design flexibility.

Key findings from this study affirm that fire remains a persistent hazard aboard cruise vessels, with engine rooms, galleys, and electrical systems posing the highest ignition risks (Xie, 2001; Rhine, 2024; Komianos, 2023). Traditional prescriptive regulations, while valuable, apply protections uniformly across all spaces, leading to potential inefficiencies in resource allocation. In contrast, risk-based fire safety design enables the prioritization of mitigation measures according to the probability and consequence of fire events—allocating resources where they are most needed.

Recent studies have shown that integrated risk assessments are not only feasible but also provide a solid foundation for design decisions, enabling the development of comprehensive models that quantify fire scenarios ship wide (Vassalos and Fan, 2016). Ships designed under risk-based principles have demonstrated superior safety performance, particularly in societal risk metrics, compared to those built using conventional prescriptive methods.

Furthermore, the evolving regulatory framework, particularly SOLAS Chapter II-2, Regulation 17 and supporting guidelines such as MSC/Circ. 1002, facilitates the approval and implementation of performance-based alternative designs. These frameworks support innovation, enabling the use of novel technologies and materials—including fire-safe applications of FRP composites—when supported by adequate risk analysis and fire protection measures (Evegren, 2010).

Based on these insights, this study recommends the following:

- Adopt risk-based design as standard practice for fire safety on cruise ships, especially in high-risk areas such as engine rooms, galleys, and electrical zones.
- Utilize comprehensive risk models that evaluate both likelihood and consequence to guide the design and placement of fire protection systems.
- Tailor passive and active protection systems to match risk levels, including advanced compartmentation strategies, AI-enhanced detection, and smart suppression systems.
- Integrate human factors and operational strategies, including risk-informed crew training, decision-support systems, and proactive maintenance planning.
- Leverage regulatory mechanisms for alternative designs to pursue innovative yet safe solutions.
- Institutionalize continuous improvement, ensuring that fire safety strategies evolve with operational data and new technological advancements.

In conclusion, risk-based fire safety design provides a more precise, effective, and forward-looking approach to protecting cruise vessels. By focusing resources on the most significant risks and embracing innovation within a structured regulatory framework, the maritime industry can achieve higher standards of safety while promoting design efficiency and operational resilience.

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