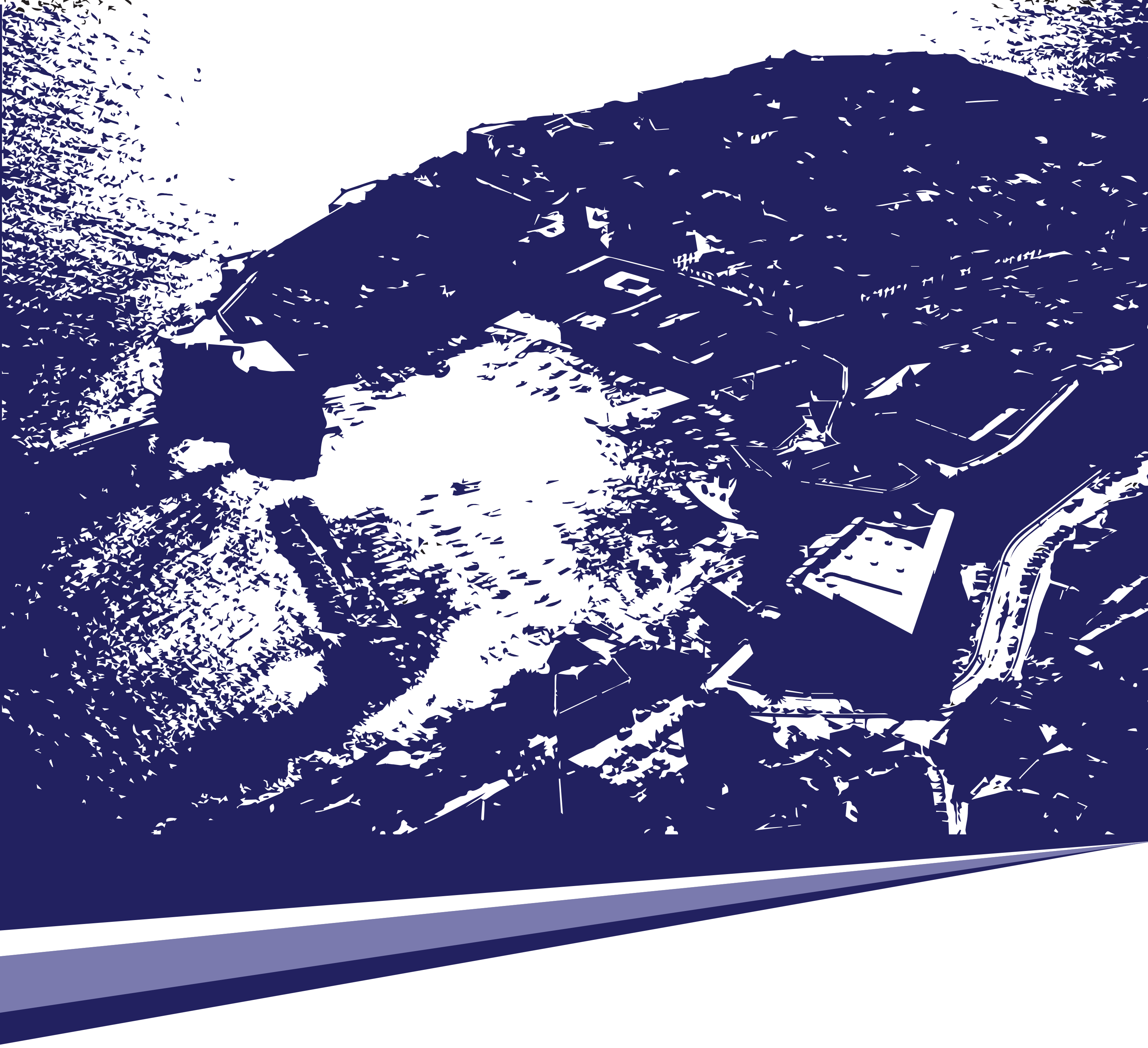

NAŠE MORE 2025

4th International Conference of Maritime Science & Technology

CONFERENCE PROCEEDINGS

SVEUČILIŠTE
U DUBROVNIKU
UNIVERSITY
OF DUBROVNIK

Dubrovnik, 18 – 19 September 2023

University of Dubrovnik
Faculty of Maritime Studies

4th International Conference of Maritime Science & Technology

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CONTENT

EVALUATING RECYCLING POTENTIAL OF ZINC IN THE MONTENEGRIN MARITIME SECTOR

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Abstract

Steel and aluminum-based metals remain the most significant materials in shipbuilding, while a wide range of different alloys are used in the production of specific maritime equipment and systems. In the context of the Sustainable Development Goals (SDGs), increasing research is being given to develop specific metal recycling loops and circular economy models. This requires the implementation of advanced safety and environmental standards. Statistical office in Montenegro has established monitoring of key recyclable metals, including steel, aluminum, copper, bronze, and brass. However, despite intensive nautical activity and maintenance service facilities, data on zinc, widely used in galvanization and corrosion protection, are absent. The lack of information on zinc quantities necessitates further research on its potential resources in the maritime sector. This paper aims to estimate the amount of zinc generated in the Montenegrin maritime industry and to assess its significance in the context of its recycling. The research methodology includes a review of the literature, direct collection of data on the generated amounts of zinc through the collection and selection in the maritime industry sector. Additionally, the chemical composition of the collected samples was characterized using scanning electron microscopy. The findings of this study represent an initial evaluation of zinc's potential to facilitate circular economy in the maritime industry. This study benefits Montenegrin maritime sector because it defines connections for the establishment of a recycling loop and specifies the potential of generated zinc.

Keywords: corrosion, zinc, recycle loop, circular economy

1. INTRODUCTION

According to the UN Agenda for 2030, the concept of sustainability is specifically related to 17 Sustainable Development Goals that represent a global framework of policies and programs whose aim is long-term, sustainable development of societies worldwide. Responsible industrial practices, the depletion of natural resources and the preservation of the environment are the issues that were mainly addressed in the past. Sustainable development is the development that meets current needs while providing the future generations with an opportunity to fulfill their own needs. In other words, sustainability and sustainable development imply balance between social justice, environmental preservation and economic progress [1].

These goals can be achieved by means of a circular approach to metal management which benefits both economy and environment. This stance was confirmed in the most recent studies, as well.

Goal 12 (responsible production and consumption) and Goal 14 (life under water) are considered are the most distinguishable in the maritime industry and shipping. The goals are primarily related to the need for a circular economy, efficient use of resources and protection of marine ecosystems from pollution and overexploitation of natural resources [2].

Preserved seas and oceans facilitate shipbuilding, maritime transport and coastal tourism. In that sense, sustainability is more than an environmental concern – it is the a major economic factor in the industry, as well. Based on the research on the behavior of marine alloys in corrosive environment, material selection and adaptation to the environment are crucial for durability and sustainability in maritime usage [3]. Likewise, probabilistic methods for the evaluation of the effects of corrosion on marine alloys detected valuable data about long-term performance of materials in various marine conditions [4].

Metals are essential for shipping due to their strength, longevity and recyclability. Shipbuilding and marine infrastructure typically exploit steel, aluminum, and copper. Zinc is, however, specific because it protects steel parts from rust. There are several methods that extend the lifespan of ship parts [5].

Cathodic protection is a process of the installation of zinc anodes on ship hulls and propeller shafts, whereby the anodes corrode instead of the base metal [6]. Zinc-based alloys, such as brass, are often used in marine pipes and valves because they are resistant to corrosion [8], while zinc oxide (ZnO) is used in antifouling coatings that prevent biofouling in the sea [7].

Probabilistic approaches to assessing corrosion in marine alloys have provided insights into long-term material performance in different marine environments [9], while solid-state recycling studies demonstrate that mechanical and microstructural properties of metals can be significantly improved through controlled recycling processes [10].

It is estimated that the annual production of zinc in the world ranges between 13 and 14 million tons, with China, Peru, Australia and the USA leading the way [11]. The importance of zinc recycling is particularly reflected in the fact that the primary production of this metal is characterized by extremely high water consumption and harmful gas emissions, as shown in Figure 1. However, it is important to emphasize that the primary production of zinc carries a significant environmental burden. Recycling, on the other hand, results in substantial savings: it enables a reduction in energy consumption of up to 76%, reduces CO_2 emissions approximately 50 times, and requires up to 190 times less water. In the European Union, recycling rates vary depending on the type of product and range from 50% to more than 90%, which clearly indicates the effectiveness of proper management of metal resources [12,13,14].

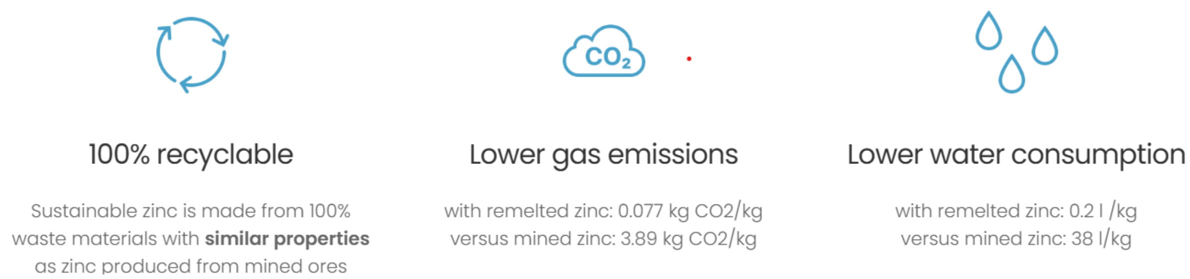


Figure 1 CO_2 Emissions and Water Consumption per Unit [14]

However, there is a significant difference between developed and smaller countries when it comes to recycling infrastructure. While industrialized countries monitor zinc from the moment of production to the end of the product's life, Montenegro still does not have a system that would enable such monitoring. Monstat tracks some other metals, but zinc is not included in the official statistics [15].

This lack of monitoring and strategy presents a serious challenge, especially considering the growth of the Montenegrin maritime sector, including shipyards like Adriatic 42. Zinc waste is generated but not recorded, and to date no study has investigated its potential for recycling in this industry. The goal of this research is to examine the possibilities of zinc recycling in the Montenegrin maritime industry. The economic, environmental and technological aspects of the recycling potential of zinc pose a key challenge in researching the circular economy of metallic materials. Given the short duration of this research and the lack of official statistical data, this paper focuses on the technical and environmental aspects of recycling, while the economic aspect is planned after data collection over one calendar year. Through field investigations, SEM analysis and institutional knowledge, the study seeks to provide guidance that can assist national strategies for circular economy and sustainable metal management.

This paper consists of five chapters. The second chapter presents a case study of Montenegro, describing zinc production, usage, and the current lack of data and infrastructure for recycling. The third chapter explains the research methodology, including sample collection, preparation, and database as well as the methods used. The fourth chapter presents the results, combining laboratory findings with data from local recycling centers to estimate zinc waste volumes and recycling potential. The fifth chapter concludes the study by summarizing key insights and offering recommendations for improving zinc management and promoting circular economy practices in Montenegro.

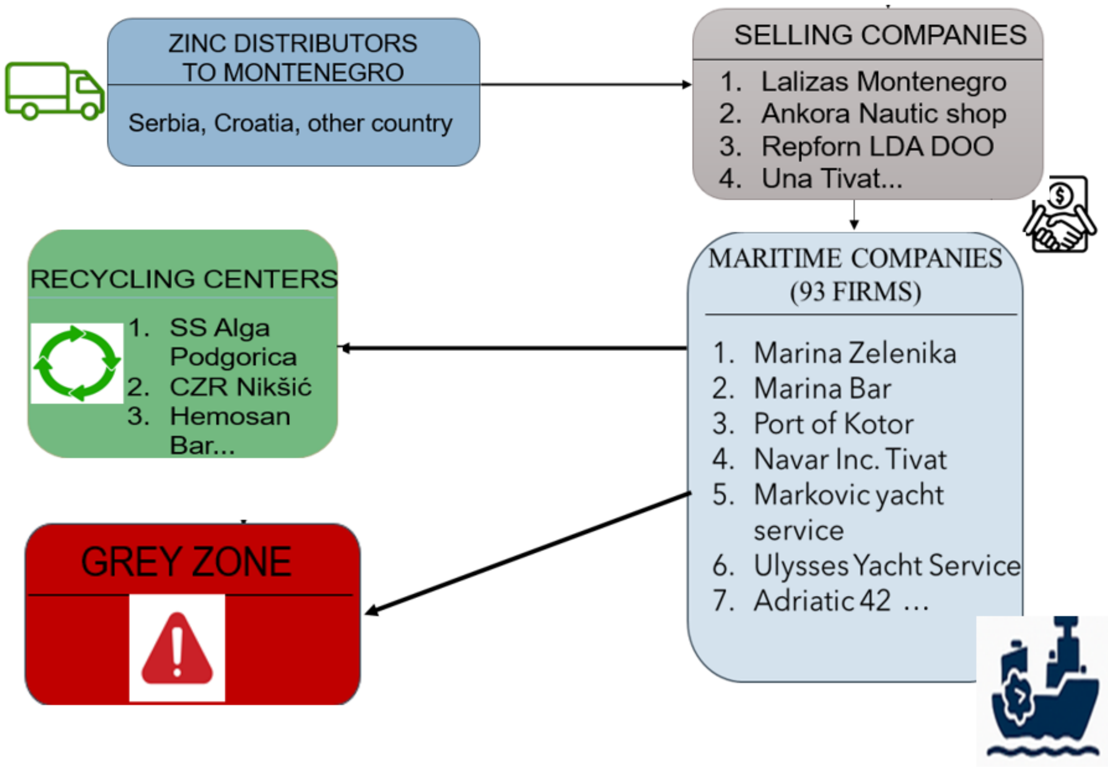
2. CASE STUDY: MONTENEGRO

In 2020, Montenegro's mining industry included the extraction of bauxite, coal (mainly lignite), construction materials, along with lead and zinc, while the processing sector produced aluminum and raw steel. The country also possesses untapped deposits of mineral resources, including metallic ores such as chromium, copper, iron, and titanium; industrial minerals such as chert, dolomite, and gypsum; and energy sources such as crude oil, natural gas, and peat [16].

Brskovo and Šuplja Stijena represent the two principal lead and zinc deposits identified in Montenegro. Between 2017 and 2020, the Šuplja Stijena Mine, managed by Gradir Montenegro d.o.o., a subsidiary of ZGH Bolesław—maintained an average annual output of approximately 2,600 metric tons of lead and 10,000 metric tons of zinc. In 2018, the Brskovo mining project was acquired by Swiss company Tara Resources AG, which subsequently finalized a preliminary economic assessment in 2019, with the results of a preliminary feasibility study anticipated in 2021. Located roughly 100 kilometers from the Montenegrin capital, Podgorica, the Brskovo Mine had previously operated from 1976 until its closure in 1991. Between 2010 and 2013, Balamara Resources Ltd., an Australian mining company, conducted exploration activities at the site. In 2014, a group of European investors purchased the project license holder, Balkan Mining Pty. Ltd., from Balamara Resources [17].

According to data from the USGS Minerals Yearbook for 2022 [18], zinc production in Montenegro, expressed as elemental zinc content, was 10,668 tons in 2018, then 9,518 tons in 2019, 10,133 tons in 2020, 9,357 tons in 2021, and 8,074 tons in 2022. These data show a gradual decline in production in the last few years, which further emphasizes the need for more efficient management of resources and the development of recycling systems.

Graph 1 present the flow of zinc from import and raw materials, through production and use, to the recycling stage at the end of the product's life. The review clearly shows how important it is to properly collect and recycle zinc to reduce waste and optimize the use of resources.



Graph 1 The flow of zinc in Montenegrin circular economy

Source: author's creation

The Statistical Office of Montenegro (MONSTAT) collects and publishes data on the production, import, export, and recycling of key metals, including steel, aluminum, copper, bronze, and brass. Their reports primarily focus on monitoring the quantities of these metals across various industrial sectors to track recycling trends and resource management. However, zinc is currently not included in metal recycling statistics, due to the lack of data and systematic monitoring [19].

In order to fill this gap, we obtained internal data from two recycling centers - RC 1 (SS Alga, Podgorica) and RC 2 (CZR Nikšić) for the period 2022-2023. These data provide valuable insight into zinc waste generation and recycling within the Montenegrin maritime sector. According to 2022 data, steel and iron dominate recycling, aluminum also plays an important role, while the quantities of copper alloys (copper, bronze, brass) and zinc remain relatively small..

In RC 1, the recycling of steel and iron completely dominates, and their quantities far exceed those of all other materials. Aluminum is also present in significant quantities, while the amount of zinc is really limited. The situation is similar in RC 2, where the total amounts of all metals are significantly smaller, and zinc is represented almost symbolically.

These data indicate that the zinc collection and recycling system is underdeveloped compared to other metals. Although zinc appears in the waste of the maritime sector, its recycling is not significant, which opens up space for process improvement, better material selection, and the introduction of specialized procedures for the collection and processing of this metal.

3. METHODOLOGY

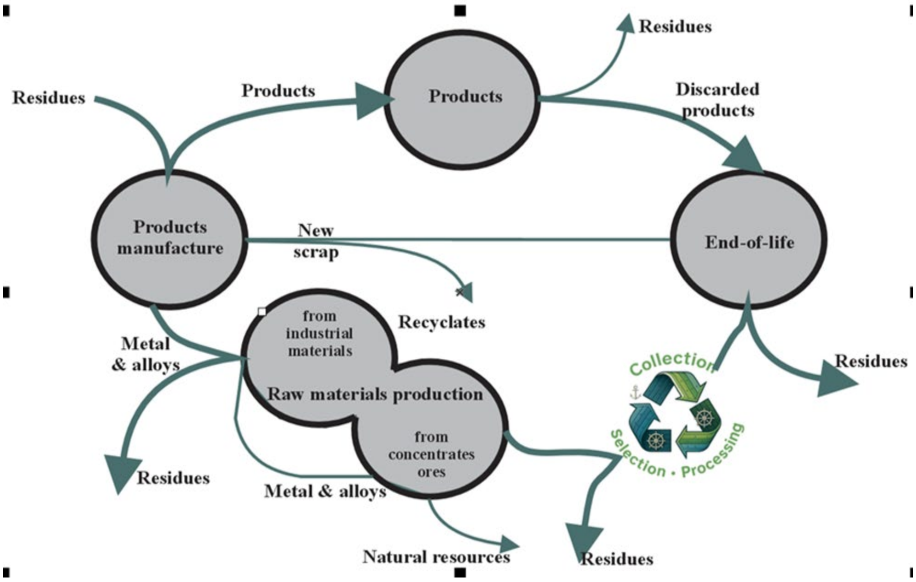
In modern society, amid growing pressures due to the depletion of natural resources and the negative impact on the environment, recycling is a key strategy for resource conservation and waste reduction.

Recycling enables the reuse of materials and reduces the need for the exploitation of new raw materials, which directly contributes to the reduction of energy consumption and harmful gas emissions.

In that sense, closed-loop supply chain (CLSC), which brings together the steps of production, application, collection of the used goods, recycling and remanufacturing is becoming increasingly important. The aim of this strategy is to reintegrate materials and components into a production cycle, thereby "closing the circle" and diminishing reliance on new resources [20].

The methodology of this study is based on the principles of circular economy and material flow monitoring. The aim of the methodology is to assed the potential for the creation of a closed recycling system in the Montenegrin maritime industry. The study was conducted through sample collection, selection, and basic processing, while the interpretation of the results was based on both descriptive and quantitative methods.

This paper uses statistical assessment and analysis as well as descriptive analysis to create an effective solution for the recycling of metal alloys in Montenegrin maritime industry in a closed cycle. A similar approach was suggested in " The Development of the recycling cycle of metal alloys in the maritime industry: a case study of Montenegro" [21].



Graph 2 The circular economy of metals – material flow [21]

Activities involving the phases of metal material collection, selection, and preparation were conducted in compliance with the circular economy's tenants and the presentation on Graph 2. For that reason, three recycling centers and seven maritime companies had bins for the selective disposal of metals. Eight zinc samples were gathered from three in three months: Adriatic 42, Yachting Service Marković, and CZR Nikšić.

Prior to in-depth analysis, every sample was appropriately labeled, cataloged, and stored in the controlled environment that preserves the structure and characteristics of the sample. This procedure enabled precise understanding of the current state of the materials and the quality selection of recycling methods. Furthermore, the method facilitated the development of a standardized closed recycling protocol adapted to the needs of the maritime industry.

Sample collection and selection ensured that zinc samples were representative and appropriate for analysis. The sites were carefully chosen to feature a variety of zinc sources whose raw materials, production methods, and applications in the maritime industry varied, as well.

The samples properly represented the materials and were classified according to appearance, size, and homogeneity. Each sample was labeled, included in a database and observed during the study to ensure traceability. This approach is in line with a larger goal - the promotion of sustainable resource management and circular economy in Montenegrin maritime sector.

During the first phase of the implementation of the EUREKA REC-MET project, key entities in the recycling loop of metal materials in Montenegro were identified, and the tentative potential of zinc was assessed. Based on the collected primary and secondary data, an assessment of the import potential of zinc in Montenegro was created, and the technical and ecological aspects of the estimated quantities of recycled zinc were evaluated.

3.1. Materials

As part of the EUREKA REC-MET project, a system of collecting metal materials based on nickel, titanium, zinc and precious metals was established in Montenegro. This research covers zinc samples collected from March to June 2025, which were located in key maritime entities in Montenegro.

The research examined the total of eight zinc samples from three different companies and from three locations across Montenegro. These samples show the diversity of zinc sources in terms of composition, industrial use and place of origin. The collection of samples lasted for 3 months, which means that the samples were representative in terms of the time of collection and condition.

The samples were collected from CZR Nikšić, Yachting Service Marković, and Adriatic 42. Three samples were taken from Yachting Service Marković, which constitutes a notable quantity of the material from the maritime industry. Four samples of zinc were taken from the Adriatic 42 location. Finally, as an extra source for analysis, one zinc sample was taken from CZR Nikšić.

The variety of samples enabled a detailed examination of the physicochemical characteristics of zinc, which is a precondition for the assessment of the recycling potential of zinc and its use in the circular economy. Different composition and origin of samples mirror varied production methods and purposes, which was significant for a deeper comprehension of the zinc flow in the Montenegrin maritime industry. Regardless of the various sources, all samples were collected through a standardized procedure, thereby lowering the risk of contamination and improving the quality of subsequent analysis. Every sample was precisely labeled and documented in order to prevent inaccuracies in tracking during the study.

Images of samples taken from various sites additionally assert the variety and unique qualities of the materials gathered. Visual aids primarily identify surface and structural characteristics of samples and additionally sustain the analysis. This method of sample collection and analysis would enhance recycling of zinc in Montenegrin maritime industry and promote sustainable resource management practices, both of which will advance the nation's circular economy.

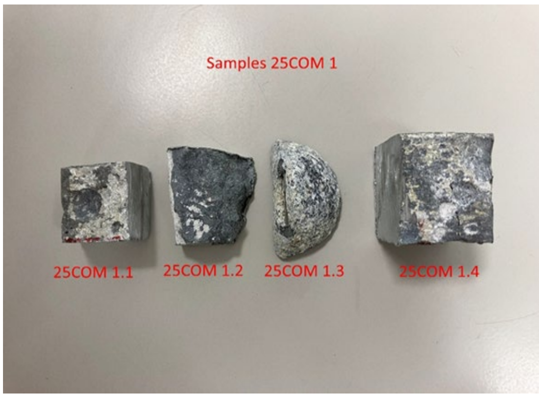


Figure 1 Adriatic 42 (4 zinc samples)

Figure 2 Yachting Service Marković (3 zinc samples)

Figure 3 CZR Nikšić (1 zinc sample)

3.2. Methods

The conducted analysis was a part of the evaluation of the metal's concentration in Montenegro and focused on the gathered and processed data on the available amounts of zinc. Based on the estimated values, the calculation of CO_2 emissions as well as water savings achieved by recycling processes to primary production was carried out. In doing so, the relevant methodological frameworks and coefficients available in the literature were used, especially the works mentioned in the introductory part of this research, which represent the reference basis for the quantification of these parameters**.**

The scanning electron microscope (SEM) is a key technique for detailed analysis of the microstructure and surface characteristics of materials, especially when studying corrosion processes. As highlighted in several studies [22,23], SEM enables extremely high spatial resolution and precise examination of surfaces, which makes it indispensable in the identification and characterization of corrosion-induced damage that often cannot be observed by standard optical microscopy.

Previous research [24,25] shows that SEM is particularly useful for the analysis of key metal parts, such as weld joint (WM), heat-affected zone (HAZ), the base material (BM), because microstructural changes often occur in these regions, which directly affects the behavior of the material in corrosive environment. Scientific literature [26] shows that the analysis of surface morphology based on SEM enables precise monitoring of the formation of pits, cracks, and other defects on the surface.

Energy dispersive spectroscopy (EDS) along with SEM are frequently used for chemical analysis of corroded surfaces. This combination allows better understanding of the composition of the oxide layer and corrosion mechanisms [27]. The identification of the components of corrosion products is crucial for the production of efficient protective coatings and for enhanced maintenance plans [28].

In addition to maritime industry, SEM also improves the assessment of metal components that were exposed to the severe marine conditions [29, 30]. A thorough SEM analysis accurately detects the types of damage and evaluate the longevity of materials, which notably advances recycling and sustainable resource management.

4. RESULTS

The results are presented in the following two sections. The first section focuses on the amount of produced and imported zinc in Montenegro, as well as the amount of water and CO2 produced during recycling. The second section shows a chemical analysis of zinc alloys obtained from Montenegrin recycling facilities and maritime businesses.

4.1. Results Assessment of zinc flow in Montenegro

Table 1 lists the importers of zinc in Montenegro, the quantities imported, and the companies that use the imported quantities of zinc. The largest importer of zinc is Serbia with an amount of 25,000 kg, while Croatia and other countries in the region recorded imports ranging from 1,000 to 2,000 kg. The companies that use this imported zinc are mainly marinas and port authorities, as well as yacht maintenance services and nautical equipment sellers. Among them, Marina Zelenika, Marina Bar, Marina Porto Novi, and Marina Porto Montenegro stand out, as well as the ports in Kotor and Bar. Also, a significant number of companies provide yacht maintenance services, while several companies operate in the sector of sales of nautical equipment and shipyards.

In total, the estimated amount of imported zinc ranges between 25,000 and 30,000 kg, which represents a significant resource for further recycling activities within the Montenegrin maritime sector.

Table 1 The importers and quantites of zinc in Montenegro

IMPORT OF ZINC INTO MONTENEGRO	IMPORTED QUANTITY	COMPANIES THAT GENERATED ZINC	TYPE OF THE COMPANY
1. Serbia	21000-25000 kg	1. Marina Zelenika	Marina
2. Croatia	1000-2000 kg	2. Marina Bar	Marina
3. Other	1000-3000 kg	3. Marina Porto Novi	Marina
		4. Marina Porto Montenegro	Marina
		5. Port of Kotor	Port
		6. Port of Bar	Port
		7. Navar Incorporated Tivat	Ship repair
		8.Markovic Yacht Service	Service
		9. Yacht Pro Service Dubreta	Service
		10. Ulysses Yacht Service	Service
		11. Adriatic 42	Shipyard
		12. Lalizas Montenegro	Sale nautical equipment
		13. Ankora Nautic Shop	Sale nautical equipment
		14. Una Montenegro	Sale nautical equipment
		15. JP "Morsko Dobro"	Public Company
		Others	
TOTAL:	22000-30000 kg		

Source: author's creation

Based on data collected from companies and recycling centers that generate zinc, the total amount of zinc generated was determined to be approximately 6,700 kg. It is estimated that about 45% of that amount is recycled, corresponding to approximately 3,015 kg of recycled zinc.

Among the entities that participate in the generation of zinc, the most significant contribution is made by Adriatic 42 with 3,000 kg, JP "Morsko Dobro" with 2,500 kg, and Navar Incorporated Tivat with 500 kg. Smaller quantities are recorded at companies such as Marina Zelenika (200 kg) and Marković Yacht Service (400 kg), while some entities, although recorded in the system, do not have reported precise quantities.

These data represent the basis for assessing the contribution of zinc recycling to the reduction of CO_2 emissions in the maritime sector of Montenegro, and enable the identification of key actors and potential points for improving the collection and recycling process.

CO_2 emissions – Results show that recycled zinc generates significantly lower CO_2 emissions compared to primary (mined) zinc. Specific emissions are 0.077 kg CO_2/kg for recycled zinc, while for mined zinc, they are 3.89 kg CO_2/kg. For the analyzed amount of 3,015 kg, emissions amount to 232.16 kg of CO_2 for recycled zinc and 11,729.35 kg of CO_2 for mined zinc. This confirms that the CO_2 emissions of recycled zinc are approximately 50 times lower.

Water consumption - Recycled zinc also shows a significant advantage in terms of water consumption. Specific consumption is 0.21 l/kg for recycled zinc, while mined zinc requires 38 l/kg. For a total quantity of 3,015 kg, this represents 603 liters for recycled zinc and 114,570 liters for mined zinc, or about 190 times less water consumption.

These results indicate the environmental advantage of using recycled zinc, both in terms of reducing greenhouse gas emissions and in terms of preserving water resources.

4.2. Results Chemical Analysis

The measurement and chemical analysis of the samples were performed using the above-mentioned SEM methods, with the samples carefully placed in the device for precise determination of the chemical composition. As an example, Figure 7 shows the measurement process of four zinc samples collected from the Adriatic 42 shipyard. The measurement and chemical analysis results obtained for these samples are presented in detail in Table 2.

The same measurement and chemical analysis procedure was applied to the remaining samples collected from other companies within the scope of the research. The results for these samples, including the determined percentages of major and minor elements, are presented in the corresponding tables (Tables 3 and 4). This approach allows for a clear presentation and comparison of the composition of samples from different sources, and facilitates the analysis of variations in material quality depending on the origin.

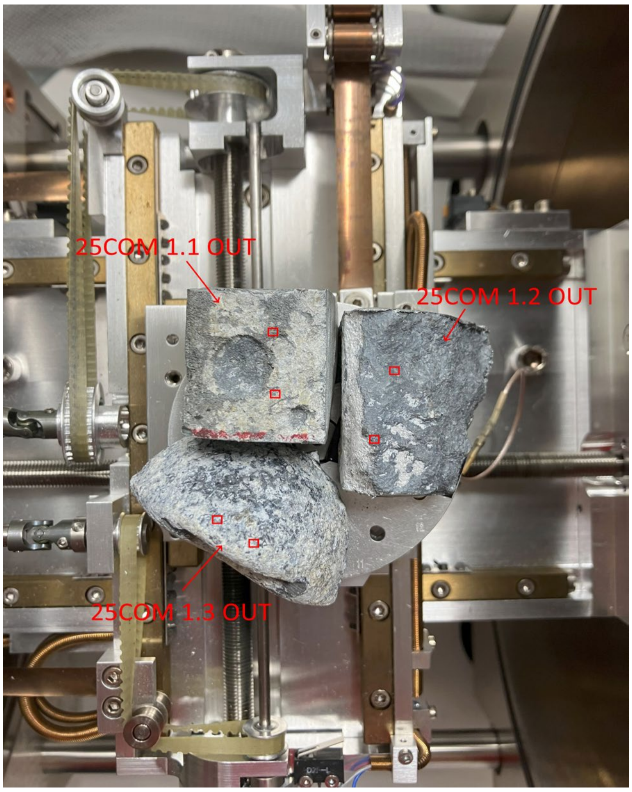


Figure 7 Measurement for zinc samples in “Adriatic 42”

Table 2 Chemical analysis for zinc samples in “Adriatic 42”

SAMPLE	CHEMICAL ELEMENT							
	O	Al	S	Zn	Si	Mg	Cl	Ca	Fe
25 COM 1.1 OUT	36.03	1.66	0.92	60.45	2.005	/	1.72	1.47	1.72
25 COM 1.2 OUT	32.16	/	/	64.02	2.41	1.74	3.52	0.91	/
25 COM 1.3 OUT	27.17	1.11	1.74	70.66	/	/	2.1	/	/
25 COM 1.4 OUT	36.18	1.33	3.31	59.45	/	/	3.71	0.36	/
AVERAGE	32.88	1.36	1.99	63.64	2.20	1.74	2.76	0.91	1.72

Table 3 Chemical analysis for zinc samples in “Yachting Service Marković”

SAMPLE	CHEMICAL ELEMENT								
	O	Al	S	Zn	Si	Mg	Cl	Ca	Fe
25 COM 2.1 OUT	30.79	1.21	2.82	60.45	1.04	/	5.64	/	/
25 COM 2.2 OUT	35.43	0.85	0.57	63.36	/	/	1.35	0.52	/
25 COM 2.3 OUT	37.29	1.96	4.41	57.73	2.40	/	4.46	1.82	1.24
25 COM 2.4 OUT	71.94	/	0.58	6.97	/	/	/	41.86	/
AVERAGE	43.86	1.34	2.09	46.62	1.72	0	3.81	14.75	1.42

Table 4 Chemical analysis for zinc samples in “CZR Nikšić”

SAMPLE	CHEMICAL ELEMENT									
	O	Al	S	Zn	Si	Mg	Cl	Ca	Fe	P
25 COM 4.1 OUT AVERAGE	47.19	2.68	2.68	40.12	3.23	/	/	1.04	1.53	2.84
25 COM 4.2 OUT AVERAGE	47.19	2.68	2.68	40.12	3.23	/	/	1.04	1.53	2.84

The results of the chemical analysis indicate that zinc on the surface of the samples retained its dominance in the composition. In addition, an increased concentration of oxygen and chloride was observed, likely due to the oxidation and corrosion processes to which the samples were exposed. These findings clearly confirm that the marine environment, rich in chloride ions and oxygen, played a crucial role in forming corrosive products and altering the chemical profile of the surface layer.

5. CONCLUSION

In this paper, for the first time, the flow of zinc through Montenegro was examined through the identification of incoming flows and the calculation of recycled quantities on an annual basis, based on the collection and selection of metal materials. In this way, a framework was established for assessing the potential of the circular economy in the area of zinc recycling.

Based on the data presented in this paper, the conclusion can be summarized in the following points:

1. This research represents the first attempt to estimate the total zinc import potential in Montenegro, which is projected to be between 25 and 30 tons per year. To date, no official data on zinc production exist in the country.

2. Based on the research conducted, it is estimated that at least 6,000 kg (6 tons) of zinc is provided annually through the secondary collection and recycling process.

3. The above shows that approximately 10–15% of Montenegro's demand for zinc could be met through recycling, which significantly contributes to resource efficiency and the principles of the circular economy.

4. Based on the calculations carried out, it can be concluded that for the amount of 3015 kg of recycled zinc, the emission amounts to 232.16 kg of CO_2. In contrast, the same amount of zinc obtained from primary production would generate 11,729.35 kg of CO_2. In terms of water consumption, recycling the same amount requires only 603 liters, while primary production would consume as much as 114,570 liters.

Future research should focus on determining the actual amounts of zinc collected in relation to the zinc content incorporated into products and assess the rate of replacement with recycled zinc versus new materials.

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COMPARATIVE ANALYSIS OF BULK CARRIERS PORT STATE CONTROL INSPECTIONS

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Abstract

Although the maritime industry is considered sufficiently regulated, vessels are constantly monitored and inspected by the Flag State (FS) and Classification Societies (CS) or Recognised Organisations (RO). Nonetheless, accidents still occur. A key risk factor contributing to maritime accidents is the existence of substandard vessels. These pose a serious threat to the safety of maritime operations, making it crucial to keep them out of traffic until they comply with international maritime regulations. One of the methods used for detecting such vessels is the Port State Control (PSC) inspection. Therefore, analysing the deficiencies identified by PSC inspections and subsequent detentions may improve safety. Bulk carriers hold the largest share of the maritime market and are the second most common type of ship involved in maritime accidents. Therefore, this paper examines the deficiencies and detentions of bulk carriers identified by the PSC inspection, highlighting the most frequent ones. The analysis uses accessible data from inspections carried out under the Paris and Tokyo Memorandums of Understanding (MoU), as well as those conducted by the US Coast Guard (USCG) and the Australian Maritime Safety Agency (AMSA). Furthermore, this paper aims to analyse the deficiencies identified during bulk carrier PSC inspections across selected regions and assess whether variations exist in the most commonly detected deficiencies. The results obtained may be used to improve and standardise the PSC inspection regime worldwide.

Keywords: maritime safety; accident; substandard vessel; deficiencies; port state control

1. INTRODUCTION

Many international conventions were adopted after major accidents at sea. The main aim of these conventions is to prevent similar unwanted accidents in the future, minimise the loss of human life at sea and ensure the safest possible transport of goods by sea. Despite the efforts of the International Maritime Organisation (IMO) and the adoption of various binding conventions, a significant number of vessels operating worldwide are not in compliance with rules and regulations. These substandard vessels represent a potential threat to other vessels and the marine environment. Vessel may be regarded as substandard if the hull, machinery, equipment or operational safety and the protection of the environment are substantially below standards required by the relevant conventions or if the crew are not in conformity with the safe manning document, owing to [1]:

- the absence of principal equipment or arrangement required by the conventions,
- substantial deterioration of the vessel or its equipment,
- non-compliance of equipment or arrangement with the relevant specification of the conventions,
- insufficiency of operational proficiency or unfamiliarity with operational procedures by the crew,
- Insufficiency of manning or insufficiency of certification of seafarers.

The Port State Control (PSC) inspections represent the only independent institution in detecting substandard vessels in the shipping industry. Unlike flag state inspection and Recognised Organisation (RO), which are nominated directly by the shipowner or ship operator, PSC is entirely independent. The importance of PSC as an institution has undergone significant changes over time. Initially, it was designed exclusively for certain states, functioning more as a substitute for flag state control. Today, PSC is a key tool in detecting and removing substandard vessels from the maritime transport sector. This is confirmed by the fact that PSC is the final element in the so-called safety net. The safety net aims to prevent the operation of vessels that do not meet the prescribed standards. There are six main elements that form the safety net [2]:

- International Maritime Organization – IMO,
- International Labour Organization – ILO,
- Flag State Control – FSC,
- Recognized organization – RO,
- Marine insurance industry,
- Port State Control – PSC.

The role of PSC within the safety net is especially relevant when examining safety records of specific ship types. Bulk carriers, the largest category of ships worldwide in terms of the number of vessels in operation, continue to face serious safety challenges. INTERCARGO data from 2015 to 2024 highlights safety issues such as cargo liquefaction, groundings, and cargo shifts as persistent risks [3]. Cargo liquefaction was the most significant cause of fatalities on bulk carriers (55 fatalities or 61.8% of the total loss of life in the period). Groundings represent the most frequent cause of ship losses, with nine losses or 45.0% of the total number of bulk carrier casualties. Cargo shift (not including liquefaction) resultes in total loss of two bulk carriers and 12 fatalities (13.5% of the total number of fatalities on bulk carriers).

Specifically during 1990-2000, the sector experienced annual losses of between 5 and 26 bulk carriers, with seafarer fatalities ranging from 23 to 186 per year. The introduction of a New Inspection Regime (NIR) and detailed analysis of maritime accidents involving bulk carriers, which determine the root causes, has contributed to a positive trend in reducing the number of ships and lives lost, as well as the number of non-compliances found on these vessels during regular PSC inspections [3].

This paper examines the five most common types of deficiencies on bulk carriers identified during PSC inspections in regions covered by the Paris and Tokyo Memoranda of Understanding (MoU), as well as those conducted by the US Coast Guard (USCG) and the Australian Maritime Safety Authority (AMSA). The deficiencies analysed pertain to the period from 2019 to 2023. After investigating and comparing the five most frequent non-compliances found across different regions, proposals are presented to improve overall crew performance and ship maintenance, which could reduce the number of deficiencies and enhance overall ship safety.

2. DEVELOPMENT AND THE ROLE OF MEMORANDUMS OF UNDERSTANDING

In response to the persistent threat posed by substandard vessels, Port State Control (PSC) has emerged as a key mechanism for ensuring compliance with international maritime regulations and enhancing navigational safety. The need for port cooperation and insight into inspections led to the establishment of the first Memorandum of Understanding on European port control, also known as the Paris Memorandum (Paris MoU), which came into force on July 1, 1982. [4]. In 1991, IMO adopted resolution A.682(17) on regional ship control cooperation to promote regional agreements. It took ten years before the second memorandum was formed, indicating slow progress in PSC. The establishment of the second memorandum served as a catalyst for the creation of other memoranda worldwide. Today, there are nine memoranda, as shown in Figure 1.

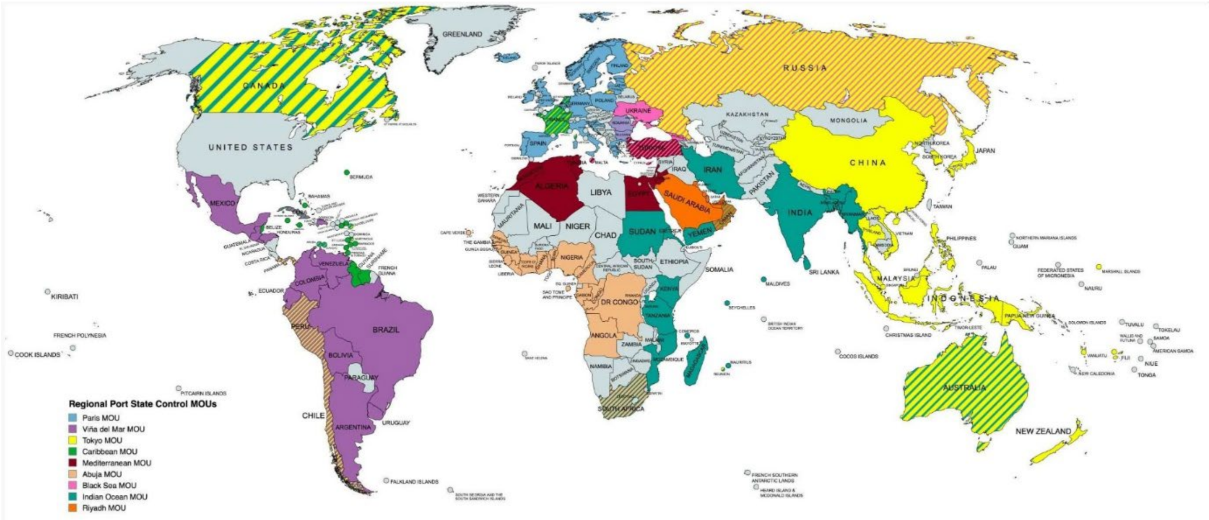

Figure 1 Regional PSC MOUs

Source: [5]:

An MoU is not an international convention; it is an administrative agreement that does not establish legally binding obligations for state parties. Its purpose is to create a framework for cooperation among the maritime authorities of a region or a group of states with a similar approach towards PSC [2].

Due to the need to define the procedure for port state control inspections, the IMO adopted Resolution A.787(19) in 1995, which provides basic guidelines for the port inspection. The currently valid resolution is A.1185(33), adopted on December 6, 2023 [6]. It is important to point out that the US Coast Guard act independently, so it can’t be described as a memorandum. Several countries are members of more than one memoranda, like Canada, Russia, or Australia.

Despite adopting various conventions, resolutions, and regulations, and with modern ships being much more technologically advanced and subject to stricter, more detailed inspections, accidents can still occur. Ensuring compliance with safe and efficient port operations is a crucial aspect of the maritime industry. For shipping companies, compliance demands additional investments and resources, which increase costs. However, non-compliance can lead to serious repercussions, including vessel detention, substantial fines, and damage to reputation. From the perspective of port authorities, compliance helps maintain a port’s competitiveness and integrity by preventing delays, accidents, and potential environmental damage. To emphasise the importance of compliance, some key facts will be highlighted [7]:

- compliance with international regulations is vital to ensure the safety of vessels, crew, and cargo,
- compliance improves the overall efficiency of the port,
- compliance can lead to cost savings over time,
- non-compliance may result in severe consequences for shipping companies.

The PSC authorities conduct inspections to verify ships' compliance with international conventions and regulations. Inspection procedures are thorough and cover various aspects of the ship's operations, including its equipment, safety, crew, and environmental compliance. These procedures are designed to identify deficiencies and non-compliance, ensuring that corrective actions are taken to address any issues. A typical inspection of ships by any PSC inspector (Figure 2) usually includes the following:

- verification of ship certificates and documents,
- assessing the condition of the ship, the ship's equipment, and the crew's competence,
- targeted inspecton of any area prioritised by inspectors.

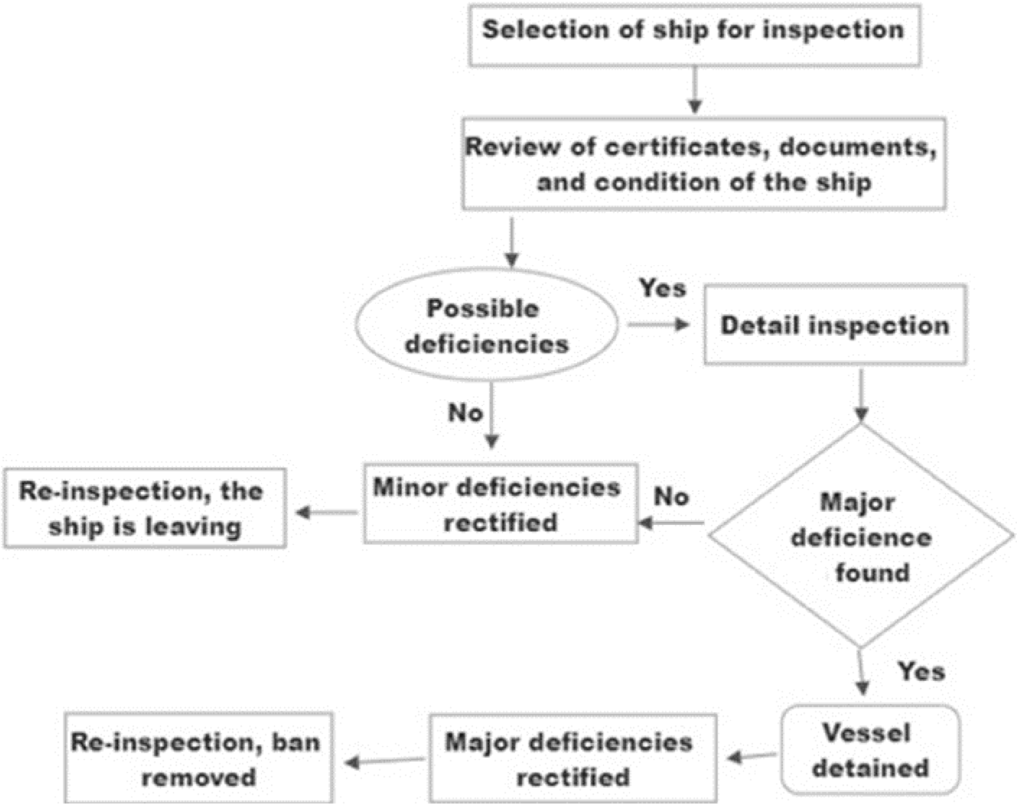

Figure 2 Common PSC inspection sequence.

Source: Authors according to [8]

These developments show that PSC, supported by regional memoranda and IMO guidelines, has become a strong framework for identifying substandard ships. Still, its effectiveness relies on ongoing data analysis, focused inspections, and adapting to vessel-specific risks, especially for high-risk ship types like bulk carriers.

3. LITERATURE REVIEW

Major maritime accidents that have occurred in recent years, resulting in the loss of human lives and causing significant material damage, have drawn attention to the condition of ships and the quality of inspections conducted. These events have led to increased interest from the academic community in the issue of substandard ships. In response, several researchers have explored various aspects of this topic, examining the prevalence of substandard vessels and the mechanisms in place to detect and prevent their operation. A comprehensive analysis, which includes inspection data recorded by the Paris MoU from 1982 to 1992, was conducted by Payoyo [9]. The author concluded that, although substandard vessels are undoubtedly present, the inspection data facilitated the identification of these vessels. They promote regional cooperation and enhance efficiency in enforcing international standards. The spread of regional memoranda significantly reduced the potential for substandard ships in international navigation, a conclusion drawn by Hara in his research [10]. Cariou et al. analysed how ship characteristics affect inspection results. They confirm that major influencing factors are ship age, type, flag, and registry [11]. Knapp and Frances examined differences between PSC regimes. They point out that the frequency of inspections should be related to ship records; in other words, ships with fewer deficiencies or detentions are less likely to be exposed to inspections. Several MOUs adopted this model later. The implementation of their proposed model and the establishment of the New Inspection Regime - NIR in 2011 resulted in a new approach to selecting ships for inspection [12]. A few years later, these researchers concluded that ship type, age, and tonnage influence the severity of maritime accidents [13]. Yang et al. conducted a comparative analysis to assess the influence of NIR on the PSC inspection system and vessel quality from both microscopic and macroscopic perspectives. They concluded that the New Inspection Regime - NIR offers a radical and significant evolution of the PSC inspection system, improving control of substandard vessels, encouraging ship owners to maintain their vessels at a high-quality level, and ultimately ensuring maritime safety [14].

Given the impact of ship characteristics, such as age, type, and flag, on both inspection outcomes and accident severity, and considering the improvements brought about by the NIR, it becomes crucial to focus on specific ship types that are especially exposed to risk. Bulk carriers, due to their structural complexity, high cargo loads, and history of serious incidents, form one such category. A targeted analysis of the most common deficiencies found on bulk carriers can offer valuable insights for further reducing substandard conditions and improving maritime safety. This aligns with the broader goal of PSC to shift from generalised inspections towards risk-based, data-driven strategies.

4. METHODOLOGY

All data analyzed in this paper are available on the official websites of the examined memoranda (Paris and Tokyo), as well as on the official websites of the USCG and AMSA. Descriptive statistical analysis was employed based on data from inspection reports during the period from 2019 to 2023. Figure 3 presents the methodology workflow.

Figure 3 Methodology workflow.

The paper presents an analysis and comparison top five deficiencies identified during inspections on bulk carrier vessels in four regions. The aims are to identify the most frequent types of deficiencies, highlight regional enforcement trends, enhance compliance strategies, and improve overall vessel safety and performance.

5. RESULTS AND DISCUSSION

According to the analysed data, it is evident that the Tokyo MoU made the largest number of inspections, as that region covers the largest area. Figure 4 gives a breakdown of the total number of inspections on bulk carriers in the period from 2019 to 2023 as per the analysed MoUs.

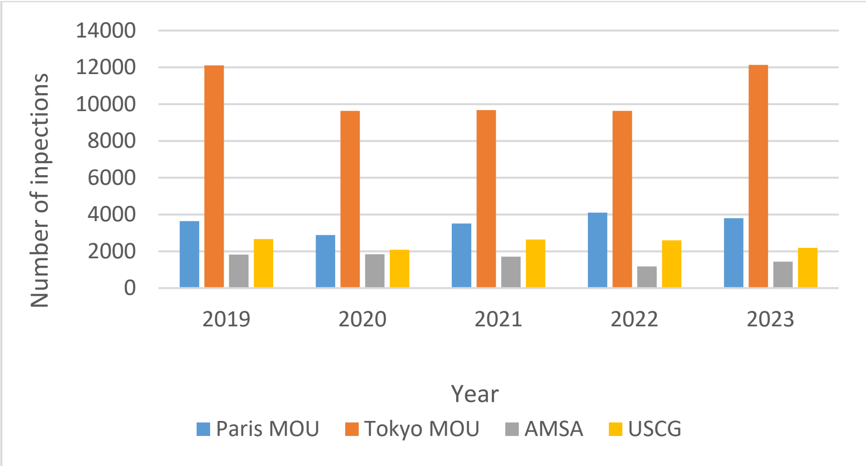

Figure 4 Number of inspections in examined regions from 2019 to 2023.
Source: Authors based on [15-18]

The proportion of deficiencies is different since the categorisations of the deficiencies found during inspections in the observed memorandum are not harmonised. Table 1 shows the total number of deficiencies and detentions detected within the examined regions during the PSC inspections on bulk carriers.

Table 1 Review of deficiencies (def.) and detentions (det.) detected during PSC inspections.

	Paris MOU		Tokyo MOU		AMSA		USCG	
	def.	det.	def.	det.	det.	det.	def.	det.
2019	876	112	44377	398	2938	107	-	28
2020	839	80	20235	231	4105	121	-	21
2021	1150	129	23619	218	4051	105	-	22
2022	1446	205	28215	247	3446	76	-	27
2023	1385	137	46337	467	4102	98	-	26

Source: Authors according to [15, 16, 17, 18]

Excluding the pandemic period, it is evident that the number of deficiencies and detentions has been constantly increasing, especially in 2023, except for the region under the Paris MoU, where both deficiencies and detentions have decreased slightly. For the USCG region, the number of deficiencies is not mentioned because that data is excluded from their reports. The negative trend of increasing non-compliance on bulk carriers persists in most regions, despite efforts by the IMO to address the issue through the adoption of numerous rules and regulations. Another negative trend is ship detentions, particularly in the Tokyo region. These facts confirm that a large number of substandard vessels are still in operation. Further analysis reveals that the category with the most deficiencies, across all observed regions, is fire safety. The five most frequent deficiencies found during PSC inspections on bulk carriers in the observed regions are given in Figure 5.

Figure 5 The top five deficiencies detected in each region from 2019 to 2023.

Source: Authors according to [15, 16, 17, 18]

Although records of detected deficiencies are not harmonised across regions, the fire safety category is almost always in the top category in all areas and poses a significant concern. It is essential to raise crew awareness about the fire risk onboard a ship. Ongoing familiarisation and training on the use and maintenance of fire-fighting equipment, along with adherence to fire safety procedures to boost fire safety awareness, should be implemented onboard ships, especially those with the highest number of deficiencies in the fire safety sub-area.

Another area with a significant share of total deficiencies is navigation safety and the general safety management system (SMS) onboard. Analysing inspection records, the proper implementation of ISM on bulk carriers remains a major concern. This poses a potential risk of unwanted incidents, such as groundings or collisions with serious consequences. Crew members should be able to easily understand the procedures and actions outlined in the ship's SMS to minimise their impact on seafarers' performance [19]. The active involvement of all crew members in the SMS, including sharing ideas, addressing onboard challenges, and maintaining open communication, especially on safety matters, helps foster a strong safety culture on board a ship, leading to fewer deficiencies and lower accident rates.

Based on the deficiencies identified during PSC inspections on bulk carriers, particular attention should be given to deficiencies related to seafarers' contracts and documentation, as well as the ship's certificates and official documents. Implementing a structured document control system is another important corrective action. Such a system should include certificates expiration dates monitoring, renewal schedules, and the completeness of both crew and ship-related documentation. The digitalisation of documents and certificates, along with secure backup procedures accessible both onboard a ship and ashore, could potentially significantly decrease the risk of oversight and enhance the reliability of documentation. Increasing seafarers' awareness and training is also important. Crew members should be advised about their responsibilities regarding personal documentation, the importance of maintaining valid certificates, and the consequences of non-compliance with these requirements. Implementing these corrective actions into standard operational practices onboard ships could substantially improve safety related records, including regulatory compliance, and at the same time minimise the number of deficiencies detected during PSC inspections.

6. CONCLUSION

The analysis of PSC inspections on bulk carriers from 2019 to 2023 highlights challenges in maritime regulatory compliance across different regions. The Tokyo MoU reported the highest number of inspections, which is expected given the size of its coverage area. Aside from the pandemic period and a slight decline in deficiencies and detentions under the Paris MoU, a negative trend persists in both deficiencies and ship detentions, especially evident in the Tokyo MoU region in 2023.

A thorough review of deficiency categories shows that fire safety remains the most common deficiency across nearly all regions. This emphasises the urgent need for improved onboard fire prevention measures, such as regular crew training, familiarisation with fire-fighting equipment, and adherence to safety procedures. The prominence of fire safety deficiencies indicates that this area continues to pose a significant risk to both vessel and crew safety.

Deficiencies in navigational safety and the implementation of the ISM Code highlight that for many bulk carriers, this remains a significant issue. Poor understanding and application of safety procedures pose serious risks, such as groundings and collisions. Therefore, it is crucial to implement a proactive safety culture that involves clear communication, active crew participation, and ongoing improvement within the framework of the SMS.

The analysis further highlights significant gaps in seafarers and shipboard documentation and certification. Developing comprehensive, structured document control systems is important for improving safety and ensuring regulatory compliance. Digitalisation (including automated alerts for expiration and renewal dates) could be the key to decreasing deficiencies during inspections. An additional important aspect is training seafarers on their responsibilities in keeping certificates and personal documents up to date.

Addressing the most frequent deficiencies is crucial for improving maritime safety and reducing the number of substandard ships in the global bulk carrier fleet.

Differences in the categorisation and documentation of deficiencies across various regional memoranda highlight the need for standardising inspection procedures. Harmonising PSC inspection methods would lead to more accurate identification and comparison of high-risk areas where common deficiencies occur. A standardised approach enables more efficient data collection and analysis worldwide, facilitating the implementation of targeted corrective actions and enhancing safety and compliance in the international maritime sector.

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CHARTING NEW WATERS: EXPLORING LEGAL AND POLICY GAPS IN MARITIME WELFARE AND SEAFARERS' RIGHTS

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Abstract

The maritime industry, a critical pillar of global trade, is fundamentally reliant on the labour and welfare of seafarers. Significant legal and policy gaps persist despite international conventions and national regulations to safeguard their rights. This research explores the systemic inadequacies in maritime welfare and seafarers' rights, examining how these gaps undermine seafarers' well-being and compromise the naval sector's sustainable growth. The study qualitatively combines empirical and doctrinal methodologies. A critical analysis of foundational international agreements, such as the Maritime Labour Convention, 2006 (MLC), and national legislation, such as the Merchant Shipping Act, 1958 (India), establishes a theoretical foundation. Case studies, interviews with shipping industry professionals, and reviews of papers from organisations such as the International Labour Organisation (ILO) and the International Maritime Organisation (IMO) are the foundation of empirical observation. Profound shortcomings in enforcement frameworks, occupational health regulations, and the availability of mental health services are exposed by the study. Also, increased automation and green laws, including IMO 2023 goals for emissions, create new challenges, commonly overlooking the human factor. The study emphasises the need for Proposals like establishing a global maritime welfare fund and implementing regional frameworks to complement the MLC, such as a harmonised legal framework with emerging issues like integrating mental health policies, fair distribution of wages and digital welfare tools. The report advocates for the maritime industry, which appreciates economic development and human dignity, by addressing these imbalances.

Keywords: Maritime Welfare, Seafarers' Rights, Maritime Labour Convention, Legal Gaps, Fatigue and Stress

1. INTRODUCTION

Seafarers' well-being is important to their health, happiness, and job performance. The Maritime Labour Convention (MLC, 2006) or the "Seafarers' Bill of Rights" seeks to preserve good working and living standards, including wages, social protection, medical treatment, protection of health, accommodation, and provision of food. It focuses on the development of the human factor of ship safety, effective maritime transport, and protection of life and the marine environment.

Although it has developed, MLC 2006 is not a solution to all the problems facing seafarers. The divergences in the national laws of flag states, port states, and countries that supply seafarers result in unpredictable application, with concerns about whether the legislative framework adequately protects seafarers' welfare at sea and on shore.

The term "seafarers' welfare" is still vague, since the International Labour Organization (ILO) has not given a definite definition. Researchers associate welfare with satisfactory living and working conditions, guarding against exploitation, and assistance to physical and mental health, as well as family welfare. Still, seafarers continue to face cost-saving measures, exploitative crewing procedures, delayed wages, absences of shore leave, and social isolation, leading some to call their work "prison with a salary."

Workplace well-being – comprising positive emotions, job satisfaction, and work-life balance – is pivotal to seafarers' motivation, safety, and retention. Yet, seafaring is uniquely demanding, with extended time away from home, solitude, and limited shore leave. Enhancing welfare definitions and maintaining uniform MLC implementation are key to protecting seafarers' rights and maintaining the maritime industry's workforce and prosperity.

The main objective of this paper is to scrutinize and critically analyze the legal and policy loopholes that continue to exist in the area of maritime welfare and the safeguarding of seafarers' rights, even with prevailing international conventions such as the Maritime Labour Convention (MLC) 2006 and domestic legislation in the form of the Merchant Shipping Act, 1958. Through an inquiry into the effectiveness, limitations, and challenges of enforcement for these frameworks, the research aims to determine why seafarers continue to face acute hardships, such as substandard working conditions, mental health emergencies, unfair treatment, and susceptibility to criminalisation. The paper strives to shed light on the systemic shortcomings that underprotect seafarers' welfare and contribute towards violations of human rights in the world maritime sector.

In addition, the paper seeks to advance useful solutions and reforms that can close the legal and policy loopholes to guarantee enhanced protection and well-being of seafarers globally. It aims to look into pioneering steps like the creation of a global maritime welfare fund, increased regional cooperation, and the integration of mental health policies and digital welfare tools within maritime law. Through the integration of doctrinal analysis, case law research, and industry stakeholders' empirical knowledge, the work hopes to drive policy-making and facilitate a maritime industry that maintains economic sustainability as well as the inherent dignity and rights of seafarers.

Since people have learnt to conquer the sea for livelihood and adventure, seafaring has its roots in the quest for survival and adventure. Due to the lack of simple access to legal protection, this job has become extremely risky. When on high seas, seafarers frequently experience legal isolation due to modifications to ship-related rules or regulations. Through word-of-mouth, the "custom of the sea" has developed and spread from ship to ship, and seafarers can discern between the proper and improper application of regulations.

Seafarers frequently protest any mistreatment, which might be physical assault, revenge, desertion, jumping ships, mutiny, staging, or an inability to work properly. To alert potential sailors, negative experiences on a particular ship are disseminated throughout ports. Leading British Admiralty Judge Lord Stowell contended in the Minerva (1825) case that mariners are inherently careless and come from a lower socioeconomic stratum, which can rarely bargain for better wages.

Seafarers are frequently treated as objects of protection rather than legal individuals with rights and legitimate expectations under laws designed for them. In its most basic form, objectification enables the "objectifier" to deny the "objectified" their humanity, rationalising their mistreatment. Because seafarers are consistently viewed and utilised as objects rather than as sentient human beings with rights and emotions, this has sparked a heated discussion about mistreatment and human rights violations.

Some officials contend that acts or behaviour directed at seafarers do not always amount to "fair or unfair treatment", but rather how laws or international rules and regulations are applied, implemented, or disregarded. According to the law, the question is not whether mariners are guilty or innocent but rather whether the "due process of law and the principles of human rights" requirement was met.

2. MAJOR EXISTING PROBLEMS RELEVANT TO SEAFARERS' WELFARE

2.1. Crew reduction resulting in fatigue and stress to seafarers

Seafarers' living and working conditions have been significantly impacted by the reduction in crew size in the twenty-first century. A standard 10,000 gross tonnes bulk carrier in the early 1970s would have had about 40 crew members. Even though a typical cargo ship grew at least three times larger by the early 2000s, it only had 18–25 crew members. The number of crew aboard ships decreased from 40–50 seamen in the 1950s to an average of 28 in the 1980s, mainly due to automation.

While experimental ships have been run with ten crews, technological advancements allow for an essential crew of seventeen sailors. Technological advancements, larger ships' increased efficiency, and the permanent shipowners' desire to reduce labour expenses are the driving forces behind the reduction of crews in the modern maritime industry. For instance, a tanker's capacity grew by 275%, yet the crew and technical expenditures only climbed by 2.68% and 25.64%, respectively. Similarly, bulk carriers' cargo capacity increased by 500%, although personnel and technical costs only rose by 4.91% and 77.82%, respectively. (Silos et al. 2012)

The minimum safe workforce should not be the standard daily manning for safe operations, but the default manning for emergencies. However, ships typically operate with a small staff for business efficiency, which means that sailors must put in long hours and work for more extended periods. Seafarers usually put in long and erratic hours because shipping is the most round-the-clock industry, which causes seafarers tiredness. The International Maritime Organization (IMO) defines fatigue as a decrease in mental and/or physical capacity brought on by cognitive, emotional, or physical activity. Lack of sleep, insufficient rest, stress, and an excessive workload are the most prevalent reasons for exhaustion that sailors are aware of.

Although the Maritime Coastguard Agency (MCA) acknowledges that weariness and seafaring are inevitable, the 1989 grounding of the Exxon Valdez was the turning point that rocked maritime society. To combat fatigue, the STCW Convention establishes mandatory minimum rest hours for all onboard personnel assigned to duty as a watch officer or rating member, as well as those whose responsibilities include designated safety, pollution prevention, and security duties.

However, sailors have not noticed any notable effects, and the maritime industry often lacks compliance. Furthermore, sailors frequently submit to port State control personnel fabricated records of their rest hours to avoid being observed or even detained by the authorities. (World Maritime University, 2020; Nautilus Federation, 2021)

Seafarers' primary concerns include fatigue at sea, stress, and workload, which can significantly negatively impact their mental health and general well-being. These days, ships' crews must manage their responsibilities with fewer crew members due to competitive voyage schedules. According to the MARTHA project, no one on board gets enough sleep, which was carried out by an international collaboration of researchers and the maritime sector. Night watchkeepers are especially vulnerable to dozing off. Compared to their crews, captains experience higher stress and exhaustion, and this can lead to long-term physical and emotional problems.

Seafarers have a six-month engagement time under the ITF Employment Agreement, which can be shortened or prolonged for operational reasons. Nonetheless, MLC 2006 permits up to a 12-month tour of duty, double the MARTHA project duration. Stress and exhaustion can harm sailors' health, happiness, and quality of life. Numerous indicators show that social isolation can also have a detrimental effect on seafarers' mental health. To protect the welfare and well-being of seafarers, these challenges must be addressed.

2.2. Impact of social isolation on the mental health of seafarers

Because they spend months at sea without interacting with anyone outside of their coworkers, seafarers are among the most solitary populations in the world. With the possibility of drowning, they frequently compare their life at sea to being in prison. One of the leading causes of psychological issues for sailors is social isolation, which can result in feelings of depression, hopelessness, anger, boredom, and exclusion. Apart from work and complete seclusion, there is seldom any social life at sea. When seafarers are denied shore vacation and social interaction for longer than four months, they often view seemingly insignificant activities as "matters of life and death." Seafarers should have reasonable access to ship-to-shore phone communications, email, and Internet facilities, if available, according to the MLC 2006. Nevertheless, this is merely a recommendation and not a requirement of the Convention. Radio communication frequencies in 1910, electronic navigation in the 1930s, and satellite navigation in the 1930s are only a few examples of the maritime sector's quick adoption of new technologies. Ships must have radars since 1974 and AIS since 2002. Although technological advancements in port infrastructure and ship design aim to increase corporate efficiency, they frequently hurt the lives of seafarers.

Many seafarers lament that even though their ships have email systems, most of them – especially ratings – do not have access to them because they are solely utilised for operational purposes. The number of crew members on board has decreased due to automation, yet the workload increases when ships are in port operations. Most seafarers find getting ashore on modern ships challenging because of their quick turnaround times and shorter port stays. Because modern ports are so far from everything – new ports are built 15 to 20 miles from cities, while old ports are placed close to city centres – shore leave is also nearly impossible.

The port state, not the shipowners, determines whether shore leave is available. Due to stringent port security regulations enforced by the International Ship and Port Facility Security (ISPS) Code, many international ports now deny shore passes to seafarers. Because they are confined to the ship's surroundings for months on end due to a lack of shore leave, sailors experience loneliness and isolation, which has a detrimental impact on their mental health and exacerbates feelings of stress, exhaustion, and despair.

2.3. Criminalisation of seafaring and unfair treatment of seamen in the event of an accident

Maritime accidents frequently cause stress and sadness in seafarers, which can result in severe mental health problems. For the remainder of their lives, they may be stigmatised by unfair treatment from foreign law enforcement. Due to the lack of binding international legislation safeguarding and advancing their fundamental labour rights following a casualty in a foreign jurisdiction, marine professionals are now denied fundamental human rights. With a noticeable trend of marine professionals facing criminal charges for mishaps beyond their control or responsibility, the repercussions for seafarers have been severe recently. The term "criminalisation of seafarers" refers to this process, which explains why maritime incidents are treated as "true crimes." As scapegoats, captains, officers, and crew members have frequently been detained without access to legal counsel or without being legally found guilty until the shipowner or the P&I club makes restitution.

One of the most significant marine pollution incidents in Pakistan occurred in August 2003 when the tanker ship 'Tasman Spirit' ran aground in a dredged channel, and the captain, six crew members, and the salvage master were charged with crimes by Pakistani authorities. The Gard explained that because Pakistan was not a party to the Convention on Civil Liability (CLC) at the time, the eight men (known as the 'Karachi eight') were detained to secure security for compensation for the pollution-related damages.

The 'Karachi Eight' were released some nine months after their arrest; nevertheless, after the United States of America (USA) and the European Union intervened, this security demand was rejected. Both officers were found guilty and given three-year prison sentences in the Hebei Spirit case in Korea when the ship's captain and chief officer were hauled ashore and imprisoned until the court trial could occur. Both officers were convicted guilty and given three-year prison sentences by the Korean Appeal Court.

Another incident involving the 'Sutton Tide' ship being arrested in Angola in March 2017 prompted Nautilus International to protest in June 2017. The ship crew, which included seafarers from Croatia, the Philippines, Russia, and Ukraine, was detained without being told the reason for the investigation after they were accused of participating in fuel theft. Crew members complained about being searched under duress and being forced to sign documents in their native tongue without being provided any explanation or rationale.

While fair treatment in criminal proceedings is a fundamental human right, sailors' right to be treated fairly in a foreign country does not directly relate to crew welfare concerns. Promoting their welfare and well-being requires that their fundamental rights be precisely protected by law. Criminalising seafarers can hurt their mental health and deter young people from pursuing careers at sea. As a result, the 2006 Guidelines on the Fair Treatment of Seafarers in the Event of a Maritime Accident were created by the International Labour Organisation (ILO) and the International Organisation of the Red Cross (IMO).

3. LEGAL ISSUES RELATING TO SEAFARERS' WELFARE

3.1. Insufficiency of maritime legislation related to seafarers' welfare

Despite being heavily regulated, the marine industry has a reactionary past. Following the Titanic catastrophe, the Convention on Safety of Life at Sea (SOLAS) was created, and following the Herald of Free Enterprise disaster, the International Safety Management (ISM) Code was ratified. However, from a human standpoint, no terrible event involving sailors has happened to warrant laws to protect their welfare. Except for the Seafarers' Wellbeing Convention No.163, which was approved by just 17 ILO member states, most international treaties do not address the well-being of seafarers.Many seafarers are overworked, underpaid, and underfed, and they have been fighting for generations to improve their lives. Their protests were put down without much interest from the maritime business, and their views were not heard. Since they live at work, necessities, including food, housing, clothes, and sanitary and medical facilities, are essential to their well-being. The inclement weather, being away from friends and family, noise, vibration, the environment, the journey cycle, port calls, cargo management, and other aspects of the contemporary shipping industry make being a sailor brutal. The International Transport Workers Federation (ITF) carries out its campaign against "flags of convenience" and frequently accuses open registries (OR) of terrible working conditions, low pay, and poor seafarer welfare. According to the ITF, many seafarers are due enormous amounts of money, and months frequently pass without indicating they received their pay.

The complete desertion of ship crews is the culmination of this immoral behaviour towards seafarers. The ILO claims that crew abandonment makes sailors into enslaved people who must rely on charity from others. Too many shipping businesses could run their ships with inadequate onboard health and social conditions and without any safety obligations due to the establishment of Open Registries in the past. Many sailors were recruited from the poorest nations because they were paid the lowest wages and were denied fundamental human rights.

Regarding the rights and welfare of seafarers, the worldwide maritime industry has seen substantial developments since the MLC 2006 was adopted and implemented. A vast array of seafarers' living and working conditions are covered by the Convention, which unifies the body of ILO law that previously existed regarding labour standards for seafarers. The MLC 2006, according to numerous industry experts, is insufficient to enhance the well-being of seafarers or address issues about basic labour and human rights, such as treating seafarers fairly in the event of a maritime catastrophe. As a result, the Convention has to be significantly revised, particularly in light of the growing concern over mental and emotional health difficulties.

3.2. The adoption and enforcement of MLC 2006

A marine labour agreement known as the MLC 2006 seeks to guarantee seafarers' rights to a safe and secure work environment, equitable employment circumstances, respectable living and working conditions aboard ships, and social, medical, and health protection. Because of the 'no more advantageous treatment clause' in Article V (7), most flag states endorsed it. According to MLC 2006, ships from non-ratifying states that enter the ports of ratifying states shall be inspected by Port State Control (PSC). Articles, regulations, and a two-part code, including mandatory and nonmandatory guidelines, make up the Convention.

The 37 earlier ILO Conventions about maritime labour standards are reflected in the five titles of MLC 2006. The Convention's implementation and enforcement fall under the collective purview of flag states, port states, and labor-supplying states. While port states are required to inspect foreign boats entering their jurisdiction, flag states must inspect and certify ships under their register by the provisions of the MLC 2006. The 'no more advantageous treatment' section of the MLC 2006 also gives the PSC the authority to investigate state ships that have not been ratified. Implementing minimal standards for the hiring and placement of seafarers and the social security protection of their citizens is under the purview of labour-supplying states.

In 2014, rules for sailors' financial security protection were added to the MLC 2006. New amendments went into effect in January 2017 to ensure that flag states provide sufficient financial security to pay the costs of seafarers' abandonment as well as claims for occupational injury-related death and disability. In order to demonstrate financial security for liabilities if the shipowner abandons the crew, ships covered by MLC 2006 must show certificates from an insurer or another financial security provider, such as Protection and Indemnity (P & I) Clubs.

3.3. Inspections of welfare issues by Port State Control

Regional Memorandums of Understanding (MOU) on Port State Control, the oldest of which was the Paris MOU, govern the regular and methodical procedure of port state inspection. One of the first conventions establishing port state inspection was the Merchant Shipping (Minimum Standards) Convention of 1976 (ILO C147). It did not, however, go into great detail on the methods and practices. Technical matters about ship safety and maritime pollution have taken precedence during a port state inspection under the International Maritime Organisation (IMO) Conventions.

Since the MLC 2006 was enacted, labour issue inspections have been a significant part of PSC activity. In order to complement flag State inspections, the Convention appears to have attempted to create a methodology and language that would blend in perfectly with the current PSC regime. According to Regulation 5.2.1, every foreign ship that calls at a Member's port may be inspected to determine if the working and living circumstances of the seafarers on board comply with the Convention's provisions, including the seafarers' rights. The Maritime Labour Certificate (MLC) and Declaration of that (DMLC) are accepted by each Member as first proof of conformity with the Convention's standards.

The following situations may necessitate a more thorough inspection to determine the working and living conditions aboard the ship: (a) the necessary documents are either not produced or are falsely maintained, or the documents that are produced do not contain the information required by this Convention or are otherwise invalid; (b) there are clear grounds to believe that the working and living conditions on board the ship do not comply with this Convention; (c) there are reasonable grounds to believe that the ship has changed the flag in order to avoid compliance with this Convention, or (d) there is a complaint alleging that certain working and living conditions on board the ship do not comply with this Convention.

The MLC 2006 has two noteworthy accomplishments in comparison to the ILO C147. First, port states may save on workforce costs and increase the efficiency of their inspections if the inspection is restricted to a check of the two documents. Second, ships may be held by the port state under the MLC 2006 if they do not comply with its requirements. The most common areas with observable inadequacies were health and safety and accident prevention (43.1%), wage payment (3.9%), ship personnel levels (28.6%), food and catering (15.4%), and lodging (10%). In order to improve ship operation efficiency, the new practice will incentivise shipowners to adhere to international labour norms.

The Montreal Convention has significantly impacted Port State control inspections on the Rights of Seafarers (MLC, 2006). Three years after it was implemented, the Paris MoU started a Concentrated Inspection Campaign (CIC) on MLC 2006, which included 3674 inspections between September and November 2016. With a minimum of 95% positive outcomes and adequate compliance, the results demonstrated that the MLC 2006 standards were implemented correctly onboard the ships. Nonetheless, 42 ships – or 1.1% of all detentions –

were taken into custody. Thirteen ships did not comply with the complaint procedure, 18 violated the seafarer's employment agreement, and 23 were detained for wage difficulties during the CIC.

The CIC on MLC 2006 revealed a startling conclusion: the ship's age is significantly correlated with its propensity to violate Convention criteria. Newer ships adhere to the Convention's criteria better than older ones. The MLC 2006 campaign demonstrates that while the percentage of ships detained for less than 15 years is negligible, breaches about inspections for the Convention's implementation increase when the ship is older than 25 years.

Between September 1st and November 30th, 2014, the Paris MOU held a CIC on "Hours of Rest" involving 4041 ships. The findings revealed that 5.1% of the watchkeeping staff did not get enough sleep, and 11.2% of the rest hours were not accurately reported. Furthermore, 16 ships were held directly from the inspections, and 27 were not human-crewed in compliance with the Minimum Safe Manning Document.

The CIC on MLC 2006 data showed a direct correlation between the ships' age and inadequacies. When the ship is over 20 years old, the percentage of detentions due to CIC topic inspections increases. However, the ratio for ships under 10 years old is very low. Inspections by the Paris MoU PSC have shown no clear link between open registries and the well-being of underprivileged seafarers. On the other hand, the trend of ratification of international conventions and favourable functioning of the findings of PSC inspections indicate that OR countries are performing well.

Compared to older vessels, newer ships are typically more compliant with international laws. This might be the case because shipowners interested in purchasing recently constructed vessels are highly proactive and want to safeguard their businesses; therefore, they do not agree to engage in risky practices that could endanger their reputation and harm their business operations. However, shipowners with older fleets appear to be more understanding regarding issues like poor shipping or unfavourable conditions for sailors on board.

The ITF's crusade against the "flags of convenience" seems pointless in the contemporary shipping industry. Since over 75% of the world's tonnage is already registered under the flag of an OR State, targeting these registries would be detrimental to the maritime industry. Numerous indicators in the shipping industry suggest that subpar circumstances and low seafarer welfare have nothing to do with the ship's flag state or the shipowner's nationality.

According to the 2016 Paris MoU annual report, most issues with living and working conditions aboard ships are connected to health, safety, and accident prevention. In actuality, 2883 cases that were pertinent to this area were documented; these cases accounted for 36.8% of all MLC 2006 inadequacies. Despite this, the shipping sector demonstrates that MLC 2006 rules are correctly implemented on board ships, as evidenced by the recent Concentrated Inspection Campaign on MLC's low detention rate.

Notwithstanding the beneficial effects of MLC 2006 on seafarers' welfare, numerous studies indicate that numerous obstacles still stand in the way of advancing seafarers' welfare. These issues are more closely linked to mariners' psychological requirements, including stress, communication with loved ones, connection, and loneliness. Even though several MLC 2006 laws directly or indirectly address each of these issues, issues about seafarers' welfare, mental health, and even fundamental labour rights are still not effectively addressed.

4. RECOMMENDATİONS

The research concentrates on the care of seafarers and the impact of maritime accidents on human rights. It presents some measures to solve the above issues. The first measure is to make the "Guidelines for the Fair Treatment of Seafarers in the Event of Maritime Accident" more powerful by converting them into a convention or treaty binding the ratifying State party. This would have provisions for sanctions and enforcement in case of non-compliance with the guidelines. The "Guidelines" requirements need to be incorporated within the new Maritime Labour Convention (MLC), making their enforcement compulsory and actionable against ratifying nations. This change would guarantee safety from unjust detention, criminalization, and other abuses of seafarers after maritime accidents.

The second recommendation is to integrate the suggested Guidelines on ensuring financial security in cases of abandonment of seafarers into the Maritime Labour Convention. This would guarantee that seafarers are never left without pay, repatriation, food, lodging, or medical attention as a result of insolvency, avoidance of responsibility, or other financial problems of shipowners. It would implement obligatory financial guarantees (e.g., insurance, bonds) for all fundamental needs and rights in cases of abandonment, filling gaps which now render many seafarers penniless and stranded in foreign ports.

The third recommendation is to create an international tribunal or agency dealing specifically with cases of human rights abuses of seafarers. Because of the intricacies and subtleties of conflict of laws, a special tribunal or court needs to be set up to address cases concerning seafarers. A specialized body would focus on maritime labour law, global standards of human rights, and transnational disputes so that decisions are uniform and verdicts are more promptly rendered.

To deal with cases or disputes relating to the enforcement of seafarers' human rights at a faster pace, a body for dispute settlement can be set up instead of a special tribunal or court. Such a body can work through expedited arbitration or mediation processes to make justice affordable, time-efficient, and accessible for seafarers who would otherwise not be able to afford long-running litigation.

Finally, coordination between labour-supplying countries, such as the European Union (EU), is recommended to require reforms on the social, human rights, and welfare fronts of their seafarers. This regional or interregional coordination may involve the establishment of joint monitoring agencies, collective bargaining forums, and common legal platforms that raise the voice of seafarers.The IMO and ILO must initiate a new campaign for ratification and signing of the SID Convention, or ILO Convention 185, guaranteeing the authenticity and autonomy of identity documents provided to seafarers. An added spur in pushing ratification and incorporation of the SID Convention would counter prevailing national security issues and implement worldwide uniformity in the verification of seafarers' identities.

5.CONCLUSION

Today, the maritime industry faces virtual slavery, terrible living conditions, starvation rations, and other types of human exploitation and degradation. The idea of slavery aboard ships has developed into a variety of abuses against seafarers. Seafarers' human rights and welfare are constantly being addressed through the approval or enactment of various domestic and international laws, legal instruments, and other policy initiatives. However, more work must be done to remedy the widespread violations of seafarers' human rights. A thorough examination of the current state of affairs in the shipping industry reveals that most international agreements and legislation designed to address and defend seafarers' rights have become toothless and ineffectual because they lack the authority or mechanism to enforce them.

The Guidelines on Fair Treatment of Seafarers in the Event of Maritime Accident, jointly adopted by the IMO Working Group and the ILO, serve as one example. This specific guideline is essentially a recommendation tool, offering state parties involved just guidance on handling the unfair treatment of seafarers in the event of maritime accidents. Adopting or implementing the guideline is entirely up to the state parties involved because it is not legally binding.

The existing state of unfair treatment and rights violations for sailors is a serious problem that needs immediate response. Failure to adopt and enforce existing laws and instruments may have made them outdated or ineffectual. Institutional changes and solutions that fall under the purview of treating seafarers reasonably are required to solve this issue. Mandatory enforcement measures and associated international punishments must be spelt out in law to require state parties or entities to implement the agreed international conventions and instruments.

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FUEL GAS SUPPLY SYSTEM OF THE ME-GI TWO-STROKE SLOW-SPEED DIESEL ENGINE IN THE LNG TANKER

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Abstract

This paper discusses the newest technologies and the operation principle of the *ME-GI* two-stroke slow-speed engine *MAN B&W 5G70ME-C9.5-GI* that is mounted on today's *LNG* tankers. The company *MAN Diesel & Turbo* has developed the *MEGI* (*M-type, Gas Injection, Electronically Controlled*) type of marine engines using both fuel oil and fuel gas. The liquified *gas boil-off* is compressed through the fuel gas supply system *FGSS* and injected into the engine cylinder combustion chambers at 300 bar and 45ºC [4],[7],[10]. In addition to safe and reliable operation on gas, the *ME-GI* (*M-type, Gas Injection, Electronically Controlled*) marine engine has significantly reduced CO_2 emissions by 20-25%, NO_x by up to 80% [7],[14]. The main purpose of the *FGSS* is to supply fuel gas to the cylinders at the correct pressure, in accordance with the engine load. The proper operation of this dual-fuel engine requires the injection of the pilot fuel, i.e. a small amount fuel oil which is self-ignited. As the engine starts running, the fuel gas (secondary fuel) is injected into the combustion chambers. The engine is always first started on fuel oil. The engine runs both on fuel oil and fuel gas with equal efficiency. The engine can operate on up to a maximum of 95% fuel gas and 5% fuel oil. The 5% fuel oil is used as pilot fuel to control the ignition of both fuel oil and fuel gas in the combustion chamber, [7],[10],[12].

Keywords: ME-GI, boil-off gas, dual fuel, fuel gas supply system

1. INTRODUCTION

The long tradition of developing technologies and advanced solutions which are aimed at finding the highest degree of fuel energy efficiency and minimal environmental pollution has resulted in modern electronically controlled marine slow-speed diesel engines using dual fuel, e.g. compressed natural gas *CNG* or liquified natural gas *LNG*, low sulphur heavy fuel oil *LSHFO*, heavy fuel oil *HFO*, low sulphur marine gas oil *LSMGO* or marine diesel oil *MDO*, [4],[7],[10].

LNG has become a desirable fuel especially after the introduction of more stringent environmental standards for reducing marine emissions, and the market for *LNG* fueled ships is expected to grow from local to deep-sea trade across the world [15].

The last *MARPOL* Annex VI sets limits for *NO*x and *SO*x emissions from exhaust gas, differentiating from open sea and selected coastal areas denominated as *Emission Control Areas ECA*. Under these conditions, *LNG* represents an efficient alternative to the conventional and more polluting fuels such as *Heavy Fuel Oil* and *Marine Diesel Oil* [12],[14].

Until now, emissions have been limited by the *International Convention for the Prevention of Pollution from Ships MARPOL*. However, new, even tighter limits have now been set, with the *Marine Environment Protection Committee MEPC* of the *International Maritime Organization IMO* adopting a decision to include a new Chapter 4 into *MARPOL*, Annex VI, referring to the *Energy Efficiency of Ships Regulations*, and introducing the *Energy Efficiency Design Index EEDI*. The *EEDI* is an important technical measure aimed at promoting more energy-efficient and therefore more environmentally friendly ships.

The *EEDI* is a measure that represents the amount of carbon dioxide CO_2 emitted when transporting one tonne of cargo per nautical mile (*tonne mile*). The *EEDI* requires the lowest possible energy consumption per tonne mile for different types of ships. In 2025, new ships, compared to those built in 2014, will be 30% more energy efficient, [7],[14].

MAN Diesel & Turbo is one the world leading manufacturers of large low speed gas diesel engines for ship propulsion, including the ME-GI series. *ME-GI* stands for M-type, Gas Injection engines – these are dual fuel, 2-stroke marine engines using both fuel oil and fuel gas, featuring the electronically controlled injection. Fuel oil is considered the basic (or pilot) fuel type, used for starting, low load operation and stopping the engine, [7],[12]. Once the pilot fuel starts the engine starts running, the fuel supply is switched to the alternative source: the fuel gas supply system delivers compressed gas to the fuel gas injection system on the engine. This means that the engine runs on compressed gas in dual fuel mode and not liquid gas [7],[12].

Compared to other dual fuel engines, the main advantage of ME-GI engines is that they always operate in a standard diesel cycle. The electronically controlled HP gas injection at the end of the compression stroke ensures the absence of limits for knocking and misfiring, *Break Mean Effective Pressure* without de-rating and possibility to operate at maximum power [10],[11],[12].

2. FUEL GAS SUPPLY SYSTEM

Heat transfer to liquefied natural gas in cargo tanks during cargo handling or during navigation leads to the formation of *boil-off gas*, the rate of cargo evaporation being in the range of 0,08 to 0,135% per day during the navigation of a loaded ship with tanks initially filled to 98,5% of their total capacity, [12],[14].

The gas vapour is taken from the vapour header and passed through the partial re-liquefaction unit and then on to the *BOG* compressor before going to the ship's main engines *ME-GI* and/or *DFDG* where it is burnt as fuel, [12].

Under normal conditions the *boil-off gas* is used as a means of fuel in the ship's main engines *ME-GI* and/or main generator engines. During normal operations the pressure in the tank is controlled by the use of the *boil-off gas* in the *ME-GI* engines or *DFDG* as fuel or in the gas combustion unit *GCU*, [10],[12]. The *FGSS* must supply fuel to all engines taking into consideration all gas supply variables.

When operating on *LNG*, the *ME-GI* engine requirements include the proper gas supply pressure (300 bar) and temperature (45°C).

The amount of gas used in dual fuel mode depends on the amount which is available from the fuel gas supply system, [7],[12]. The fuel gas supply system provides the *ECS Engine control system* with the information on the available amount of fuel gas and the needed amount of fuel oil is calculated following this information.

2.1. BOG Compressor

Compared to *HP* cryogenic pumps, high pressure *HP* compressors are costly machines, but they offer a direct solution to the *BOG* handling problem. *MAN* and *Burckhardt Compression* have been developing *BOG HP* compressor systems for *LNG* carriers with *ME-GI* propulsion. Their configurations feature the *HP Fuel Gas Supply System* integrated with re-liquefaction processes [2],[3],[6].

The *Burckhardt Compressor,* commercially labeled as *Laby-GI*, is a five-stage reciprocating machine, with the labyrinth oil-free piston sealing for the first three stages and conventional lubricated piston ring sealing in the last two stages, model *5LP250-5B-1*, see figure 1, [8],[9],[13].

The main purpose of the high pressure compressor *FGSS* is to provide fuel gas to the two-stroke main engines according to engine load and to serve *DFGE* and partial re-liquefaction plant.

The compressor unit is used to handle *boil-off gas* with a design inlet flow of approx. 4700 kg/h and will compress the gas over five stages from a suction pressure varying between 106 to 170 kPa a at variable suction temperature between -120/40°C to a delivery pressure of about 30600 kPa at 45°C, [4],[18].

The compressor may run at full or at partial load condition. The compressor can work at a different capacity, by activation of valve unloaders (100%,75%, 50%), [8].

Discharge pressure is controlled by a bypass (a recycle) valve over the first stage. Depending on the gas demand of the *MEGI* the by-pass over 1st stage opens and closes.

In case of low pressure at compressor inlet the by-pass valve over 1st stage will be forced to open to avoid vacuum in tank. The intermediate pressures are controlled with additional bypass valves over 1-3 stage and 3-5 stage, [8],[9],[13].

In the third stage a supply line is provided for supplying gas to the *Dual fuel Generators* and *GCU*. The line pressure is controlled by a pressure control valve.

The compressors, the unit vessels and piping systems are protected from unexpected overpressure conditions by means of mechanical safety valves installed in the piping system and at the compressor frame, [5],[7],[10].

Figure 1 Burckhardt Compressor, model *5LP250-5B-1*

Source: Authors, 2023.

3. FUEL GAS INJECTION SYSTEM

Fuel gas injection system is the common denomination for the fuel gas components installed on the engine, see figure 2.

The main components are:

- fuel gas pipes,
- fuel gas adapter block (connected to the fuel gas control block),

- fuel gas control block (located next to the cylinder cover),
- fuel gas injection valve (in the cylinder cover), [10],[12].

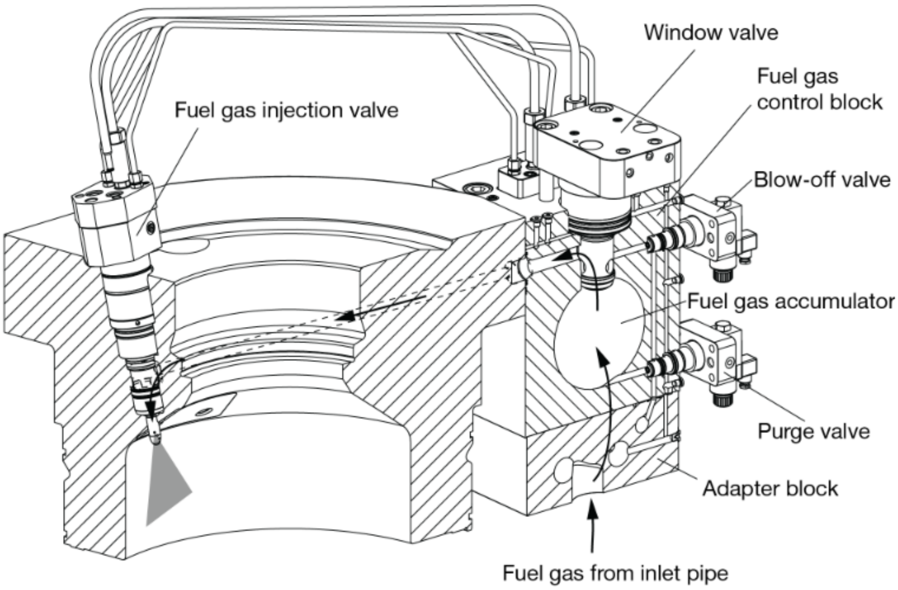

Figure 2 Fuel gas components

Source: MAN Diesel & Turbo, Manual Instruction, MAN B&W ME/ME-C-GI, Teglholmsgade 41 DK-2450 Copenhagen, Denmark, 2016.

3.1. Fuel gas pipes

There are two strings or lines of interconnected fuel gas pipes on the engine, an inlet line and an outlet line, see figure 3.

Figure 3 Fuel gas pipes

Source: Authors, 2023.

The fuel gas pipes feature double walls. The outer pipe is designed as a shield preventing gas outflow to the machinery spaces in case of a leak or rupture of the inner fuel gas pipe. The outer volume of the fuel gas pipe, including also the space around valves, flanges, etc., is ventilated by the outer pipe ventilation system, [7],[12].

The essential purpose of the outer pipe ventilation system is to provide constant air ventilation of the outer volume of the double-wall fuel gas pipe system. Ventilation is ensured by means of an electrically driven extractor fan mounted above the deck. The start, stop and operation is controlled by the *ECS*, and the system works independently of any other fan installation in the engine room.

The fan draws air through the outer volume of the double-wall fuel gas pipe, which means that the air pressure in the outer volume of the double-wall fuel gas pipe is below atmospheric pressure during fan operation, [10],[11],[12].

If any gas leaks, it will be conducted to the ventilated part of the double-wall piping system and will be detected by hydrocarbon *HC* sensors. At high leakage level the engine will continue running, but it will switch to fuel oil running mode. The fuel gas operation will discontinue and all pipes will be purged with inert gas.

The inert gas system is used for purging of all fuel gas piping in the installation. The purging pressure is engine, typical values are in the range of 10 ± 2 bar.

The first of the inlet pipes is, a vibration compensator (helix) pipe connected to the fuel gas supply pipe in one end and (via a second pipe) to an adapter block in the other end, see figure 4.

There is a bore in the adapter block which allows the fuel gas to flow freely to the next pipe in the line. The subsequent pipes are interconnecting the adapter blocks between two cylinder units. In this way the fuel gas is distributed to all adapter blocks on all cylinder units. The inlet line is the one closest to the cylinders, the outlet line is the one farthest away from the cylinders.

The interconnecting pipes are connected to the adapter blocks similarly to the inlet line pipes. The adapter blocks have similar bores which allows the fuel gas to flow freely to the next pipe in the line, [7],[12].

The outlet line on the engine ends, in a compensator (helix) pipe which is connected to an outlet pipe leading to a non-return valve and a silencer which emit exhaust in a safe area in free open space.

From the adapter blocks the gas flows to the connected gas control blocks, through control valves in the block and through bores in the cylinder covers to the fuel gas injection valves, [7],[12].

Figure 4 Helix pipe – compensator

Source: Authors, 2023.

3.2. Fuel gas adapter block

The adapter blocks are separate blocks but connected/bolted to the fuel gas control blocks with seals and guide pins between the blocks flanges. The mediums/systems are connected to the fuel gas control block through bores with seals at the blocks flanges, [7],[12].

The medium/systems are:

- gas inlet (fuel gas inner pipe),
- gas outlet (fuel gas inner pipe),
- outer pipe ventilation system (fuel gas outer pipe),
- hydraulic oil high pressure line,
- hydraulic oil low pressure supply *LPS* line,
- hydraulic oil drain from the top of the control block (the drip pan), connected, to the
- sludge/waste tank,
- sealing oil,
- hydraulic oil drain pipes, connected to the hydraulic oil drain in the *HCU*.

All adapter blocks except one type are similar, the special type is marked *End Block*, the end block has extra bores for the outer pipe ventilation system, it connects the inlet side to the outlet side in order for the ventilation air to pass, [10],[11],[12].

3.3. Fuel gas control block

The fuel gas control block contains all components necessary to control the fuel gas injection except for the fuel gas injection valves which are mounted in the cylinder cover. All the valves in the block are controlled by the *ECS*. The fuel gas control block also contains a fuel gas accumulator volume which ensures a stable fuel gas injection pressure.

The fuel gas enters the control block through a bore in the flange between the adapter block and the control block, see figure 5. from there the fuel gas enters the accumulator through a non-return valve, [7],[12].

The fuel gas injection is controlled by two valves in series. The first valve, called window valve, is normally closed. The window valve sets up a timing window (a predetermined number of crankshaft degrees) according to the crankshaft position in which it opens and allows fuel gas to flow from the accumulator through bores in the control block and cylinder cover to the fuel gas injection valves, which are the second valves in the series.

The purpose of the window valve is to function as a safety valve, it prevents that a fuel gas injection can take place outside the allowed timing window, thereby preventing an *un-timed combustion*, [7],[12].

Due to the maximum allowed open time/degrees the window valve limits the maximum possible amount of injected fuel gas. The fuel gas injection valve controls the precise timing and gas injection amount.

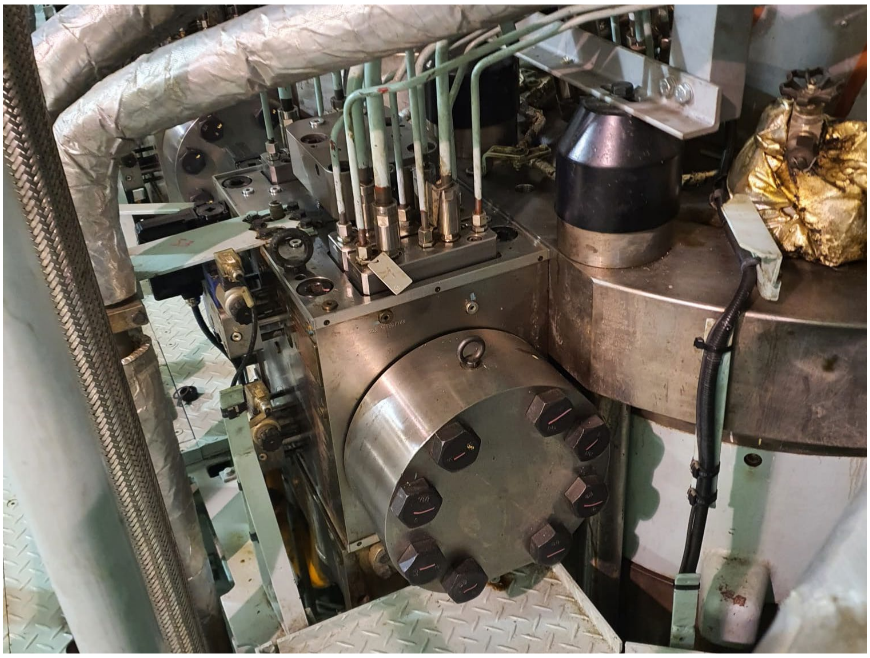

Figure 5 Fuel gas control block

Source: Authors, 2023.

The window valve, see figure 6. and the fuel gas injection valves are activated hydraulically by two electrically controlled 3/2-way valves which are controlled by the *ECS*. The window valve hydraulic activation is performed by an *ELWI* valve - *Electronic Window valve* mounted on the foremost side of the control block, [7],[12].

Figure 6 Window valve

Source: Authors, 2023.

An *ELGI Electronic Gas Injection* valve hydraulically activates the fuel gas injection. The valve supplies high-pressure hydraulic oil to the fuel gas injection valve. It controls the timing and opening area of the fuel gas valve. The *ELGI* valve cannot operate unless the *ELWI* valve is open/active. The *ELGI* is mounted on the control block on the maneuvering side. A pressure transducer connected to the *ECS* measures the fuel gas pressure in the control block bore between the window valve and fuel gas injection valves. The transducer output is used for monitoring by the *ECS Engine control system*, see figure 7.

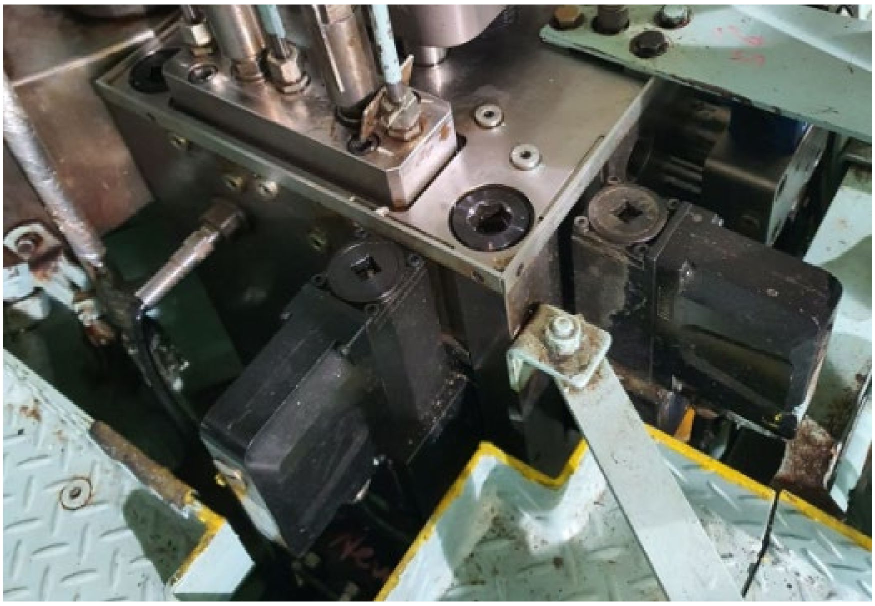

Figure 7 ELWI valve Electronic Window valve, ELGI valve Electronic Gas Injection valve and Pressure Transducer

Source: Authors, 2023.

The hydraulic oil used for activation of the valves comes from the hydraulic system's high pressure line. In order to avoid contamination of the hydraulic oil by fuel gas, the window valve and the fuel gas injection valves are supplied with sealing oil [7],[12].

The sealing oil seals the area between the fuel gas and the hydraulic oil used for activation of the valves. The sealing oil pressure is kept at a constant differential pressure above the gas pressure.

The low pressure supply *LPS* oil from the hydraulic system supplies the sealing oil whose operating pressure is 20 - 25 bar higher than the gas pressure. In this way, contamination of the hydraulic oil by gas is prevented. The sealing oil is injected into the combustion chamber together with the fuel gas. The consumption of sealing oil is small, approximately 0,135 g/kWh [10],[12].

Two solenoid controlled hydraulic directional valves, purge valve and blow-off valve, are mounted on the maneuvering side of the block, see figure 8. The valves are operated during purge and blow-off operations. If the purge valve opens it will empty the gas in the accumulator into the outlet pipe. If the blow-off valve opens, it will empty the gas in the area from the window valve to the fuel gas injection valves into the outlet pipe, [7],[12].

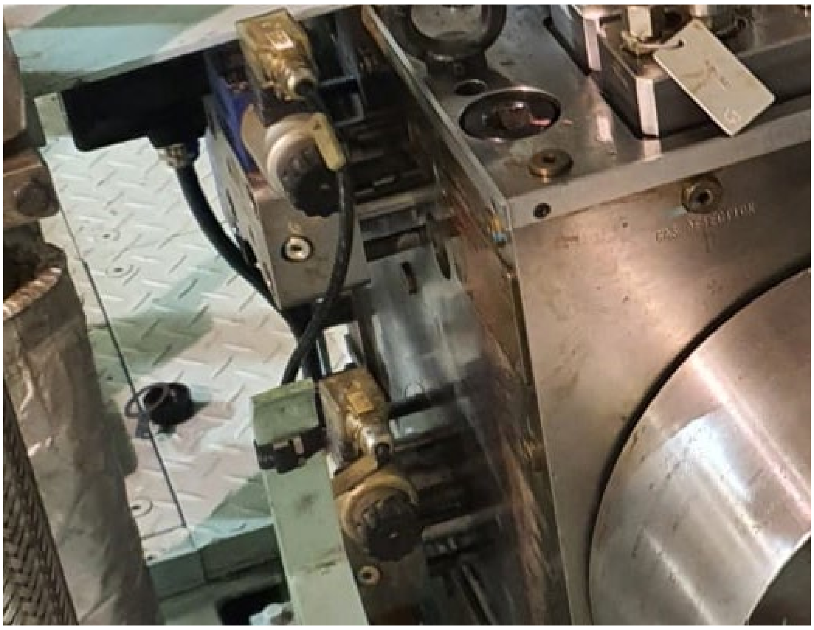

Figure 8 Blow-off valve and Purge valve

Source: Authors, 2023.

3.4. Fuel gas injection valve

The cylinder cover features three fuel gas injection valves. The fuel gas flows from the control block to the fuel gas injection valves through passages bored in the cylinder cover. Five pipes with common flanges in both ends connects each fuel gas injection valve with the control block, see figure 9.

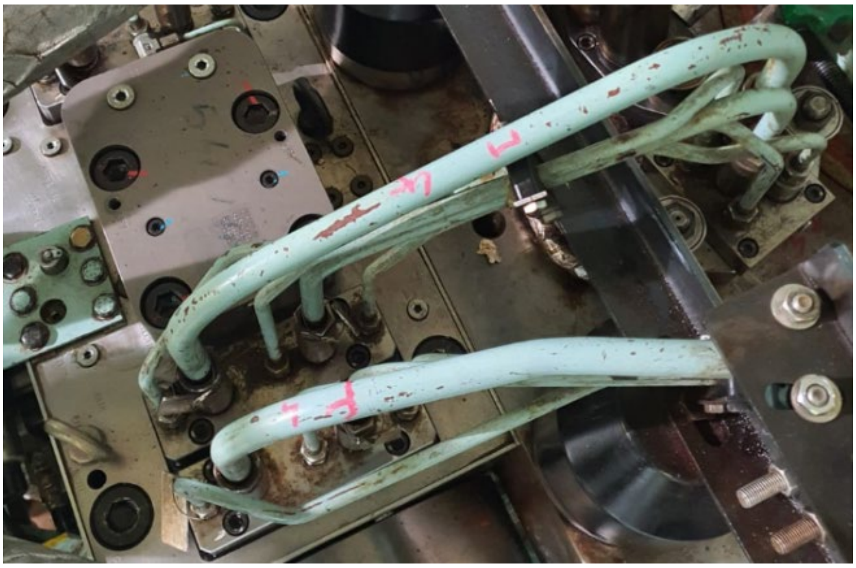

Figure 9 Five the control pipes

Source: Authors, 2023.

The hydraulic system on the *ME-GI* engine is an electronically controlled mechanical hydraulic system used for actuation of fuel oil injection, fuel gas injection and exhaust valves. The *engine control system ECS*, controls and monitors the system, [11],[12].

The control pipes are used for:

- high-pressure hydraulic oil for activation of the fuel gas injection valve. It controls the timing and opening area of the fuel gas valve, the control pressure being approximately 273 bar,
- sealing oil is applied to the fuel gas injection valves, in order to avoid contamination of the hydraulic oil by fuel gas. The sealing oil seals the area between the fuel gas and the hydraulic oil used for activation of the valves. The sealing oil pressure is kept at a constant differential pressure above the gas pressure, the control pressure being approximately 338 bar,
- hydraulic oil low pressure supply *LPS*, control pressure 4 bar, oil from the hydraulic oil low pressure supply *LPS* line is applied to the fuel gas injection valve in order to bleed the hydraulic system from air,
- hydraulic oil drain, drain oil from the valve activation and *LPS* supply is connected to the hydraulic oil drain in the *HCU*,
- gas detection, sealed areas in the fuel gas injection valve have fuel gas detection bores used for leak detection which are connected to the outer pipe ventilation system. If any gas leaks, it is conducted to the ventilated part of the double-wall piping system and is detected by hydrocarbon *HC* sensors. The detection of leakages is to be carried out when the fuel gas supply system is pressurized with nitrogen. If a leakage in the fuel gas pipe system occurs, the *ECS* will detect that there is a leakage in the system, but will not determine the location. In order to detect the exact location of a leakage, the 10 - 300/400 bar nitrogen supply or the nitrogen booster unit is used for leakage troubleshooting [7],[10],[12].

4. CONCLUSION

Designed by *MAN B&W*, *ME-GI* concept represents an environmentally beneficial solution that sets new industrial standards for two-stroke propulsion engines in *LNG* carriers and other areas of modern commercial shipping trade. The diesel-type combustion of the *ME-GI* engine, in combination with the sophisticated and reliable high-pressure *HP* gas supply system, results in superior features of these *MAN B&W* two-stroke engines. The latter have the highly flexible nature regarding the calorific value of the gas and the ability to run on almost any fuel gas quality with no or limited decrease in efficiency, [7].

Whenever the vessel enters either a harbour or an emission control area *ECA*, the multi-fueled *ME-GI* engine changes reliably and seamlessly between operating on fuel gas and *ECA* compliant fuel. Modern electronically controlled marine low-speed diesel engines using dual fuel show a significant advantage in optimizing the combustion process and represent a major step forward in efficiency and reducing harmful exhaust emissions, [4],[10],[15]. The NO_x emission control level according to regulations 13.3, 13.4, Annex VI of the *MARPOL Convention* is 17,0 and 14,4 g/kWh.

In line with these regulations, the *NO*x emission of any marine diesel engine installed in a ship constructed on or after the 1st of January 2016 must not exceed the so-called Tier III level when operating inside a *NO*x emission control area (*NO*x *ECA*) designated before 2016. For engines with a speed lower than 130 rpm, the Tier III level is 3.4 g/kWh. The high-pressure natural gas injection system used in the *ME-GI* engine designed by *MAN Diesel & Turbo* has the advantage of being insensitive to the type or variations in the composition of the gas mixture, [10],[12],[14].

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INTERNATIONAL SAFETY MANAGEMENT CODE IN MARITIME EDUCATION AND TRAINING

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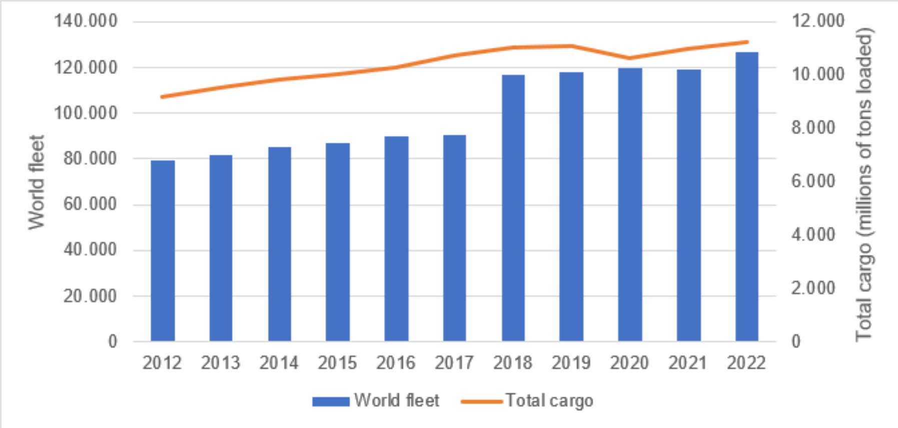
Abstract

Considering the significance of the maritime economy in facilitating global trade and advancing globalization, it is crucial to ensure, as much as possible, safe, efficient, and environmentally friendly maritime transportation without accidents. Even though and despite continuous and considerable efforts made by the International Maritime Organization (IMO) towards technical progress and the recommendations to enhance safety at sea, a significant number of accidents continue to happen. Many studies indicate that human factor is the primary cause of most accidents at sea, constituting a substantial percentage. To reduce the number of accidents caused by human factor, the International Safety Management Code (ISM) was introduced, aiming to obtain an understandable safety culture. To properly implement the requirements of the ISM Code, it is essential to understand the importance of acquiring knowledge of the Code, starting with formal education. The aim of the research is to examine and analyse students' understanding, familiarity and knowledge of the ISM Code. Based on the results, guidelines for improving the significance of the ISM Code in Maritime Education and Training (MET) are provided.

Keywords: ISM Code, maritime education and training, safety at sea, human factor

1. INTRODUCTION

Maritime transport is constantly increasing and represents the backbone of international trade and the globalization process, accounting for more than 80% of world trade volume [1]. With the continuous increase in maritime trade, there is a strong correlation with the increase in maritime traffic (Graph 1).



Graph 1 Correlation between the world fleet and total cargo

Source: [1] [2]

The increase in maritime transport is causally linked to the increase in the risk of accidents at sea [3]. The highest percentage (75 to 96%) of all maritime accidents is due to human factors [4]. The role of human factors in the maritime industry is evident in research where authors analyse 135 marine accident reports recorded in the UK Marine Accident Investigation Branch (MAIB) database. The research results indicate that human factor is the primary cause of the investigated accidents [5].

To reduce accidents caused by human factor, the IMO adopted the ISM Code in 1993, which came into force in 1998 and became mandatory through the Safety of Life at Sea Convention (SOLAS) [6]. The ISM Code aims to create an international standard for the safe management and operation of ships and for pollution prevention. The objectives of the ISM Code are to ensure safety at sea in general, and more precisely to prevent injury and loss of life, loss of property, and to prevent damage to the marine environment. The ISM required a company to develop a documented system known as a Safety Management System (SMS). The SMS is an important aspect that describes the essential policies, practices and procedures that need to be followed to ensure the safe operation of ships at sea. Implementation of the ISM Code onboard ships and in companies aiming to reduce accidents at sea, especially those caused by human factor, has proven to be effective [7].

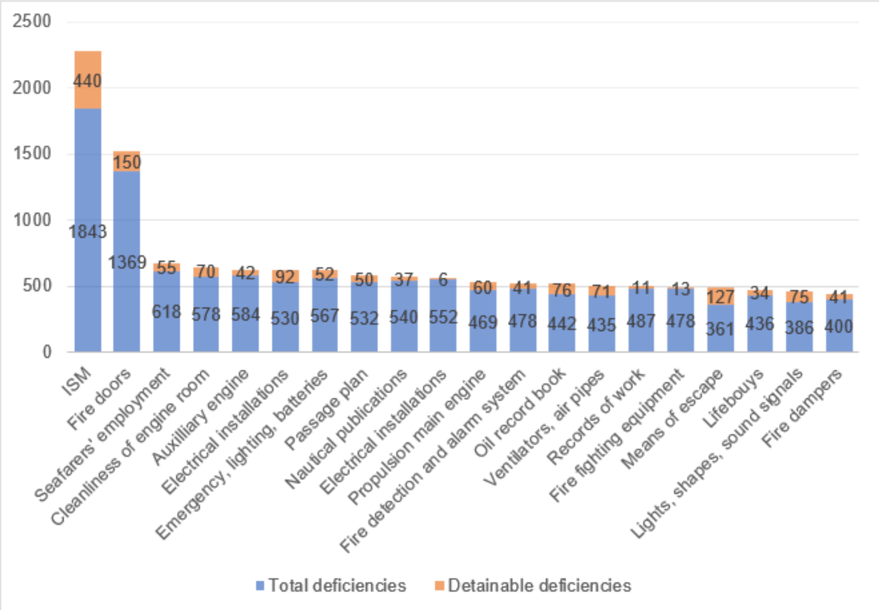
Nowadays, despite the fact that the ISM Code has been implemented, formal education or training of seafarers about the Code has not yet been established as a mandatory requirement. The STCW Convention, which serves as a binding instrument for MET standards, does not include clear requirements and standards for the education precisely related to ISM Code education and training.

Therefore, it could be considered that implementing an understanding of the importance and knowledge of the ISM Code is crucial from the very beginning of their MET.

The paper aims to find the areas for improvement in the MET system related to ISM Code education, primarily by examination and analysis of students' understanding and knowledge of the ISM Code and to draw up guidelines on how to improve the importance of representing the ISM Code topics in MET.

2. BACKGROUND

The introduction of the ISM Code in the maritime industry has undoubtedly contributed to increased safety, but there is still room for improvement. Recent data on accidents could be found in European Maritime Safety Agency (EMSA) statistical reports which show that human actions were responsible for 59.6% of accident events, and 68.3% of contributing factors were related to human behaviour (period 2014. – 2021.) [8]. Considering both the cause, human action and contributing factors related to human behaviour, the overall human factor played a role in 81.1% of the marine casualties and incidents investigated [9]. It is in line with the numbers that could be commonly noticeable in the shipping industry [8]. The Safety Digest report published by the MAIB indicates that a major factor in all maritime accidents is human failure to follow safety management protocols [10]. The research results indicate that lack of knowledge, misunderstanding, ignoring or not following safety procedures and instructions of the ISM Code are the causal consequences of accidents at sea. Furthermore, many studies indicate that poor system implementation is one of the leading problems associated with the ISM Code [11] [12]. A good indicator of misunderstanding, ignoring or not following safety procedures and instructions of the ISM Code can be visible in Port State Control (PSC) inspections. From the Paris MOU inspection database in 2023, a total of 47,510 deficiencies were found, out of which 4,809 were detainable [13]. The largest number of all deficiencies was related to the ISM Code (Graph 2).



Graph 2 Top 20 Deficiencies from the Paris MOU in 2023

Source: [13]

On top of that, the correlation between human factors in maritime accidents and the ISM Code is evident in the study by authors Batalden and Sydnes, where they analyze 94 maritime cases investigated by the MAIB [14]. The research has shown that the main challenge in implementing the ISM Code lies in the development of plans for ship operations, local management, on board and the company's ability to check whether these practices deviate from best practice or required standards.

In the research paper [15], a survey was conducted among seafarers and maritime experts with questions related to their knowledge of the ISM Code and the inclusion of the ISM Code in maritime education and training. The results indicate that there is a lack of MET requirements and programs on ISM Code topics. To underline the importance of understanding and proper implementation of the ISM Code, one of the most essential activities inevitable could be acquiring knowledge from the beginning stage of seafarers' education, starting with implementation throughout maritime university programs.

3. METHODOLOGY AND RESULTS

The research methodology in this paper is based on a survey. The target population consisted of final-year undergraduate and graduate students from Maritime faculties in the Republic of Croatia. 182 final-year students participated in the survey who, after graduating, will be ready to sea and start their sea career as apprentices.

The survey consists of 11 questions. The questions were closed-type, where respondents could choose answers from a limited set of options. The questions relating to personal opinions on the ISM Code used a Likert scale, while the questions relating to general questions on the ISM Code required respondents to select one of the predetermined answers.

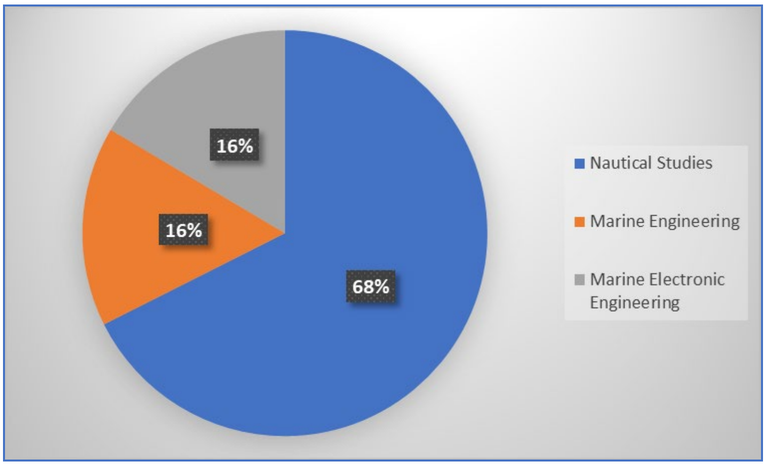
The survey consists of 3 parts related to:

- student's current academic program,
- personal opinions related to the ISM Code,
- general questions about the ISM Code.

The survey questions and corresponding results are presented below:

Questions related to the student's current academic program:

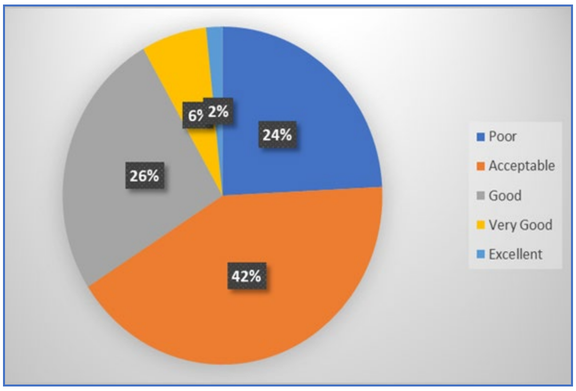
1. What is your current academic program?



Graph 3 Students distribution by academic program

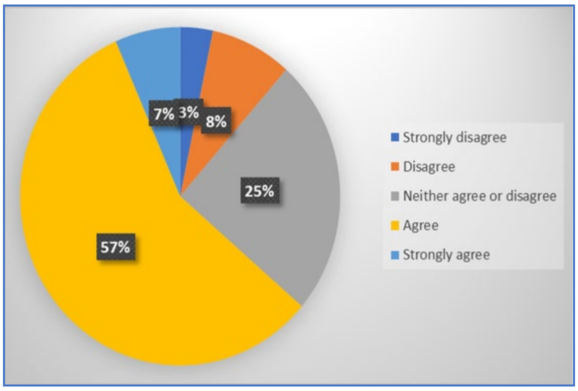
Questions related to personal opinions connected to the ISM Code:

1. In my opinion, my level of knowledge about the ISM Code is?



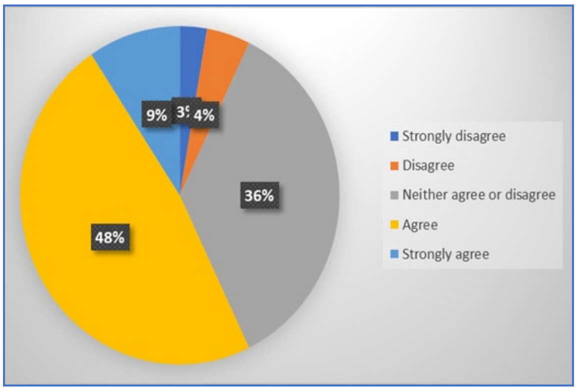
Graph 4 Distribution of students' opinion of their level of knowledge regarding the ISM Code

2. In my opinion, I received sufficient information about the ISM Code during formal education.



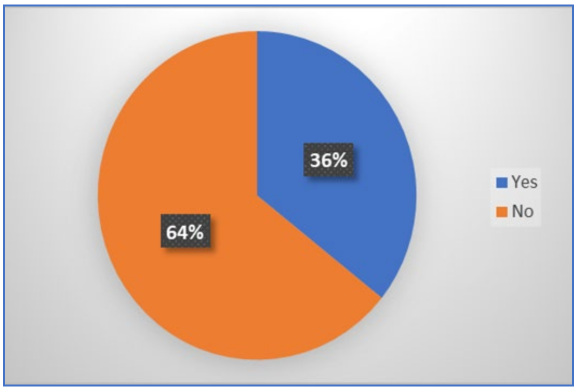
Graph 5 Distribution of students' opinions of their received information during formal education

3. In my opinion, an individual mandatory course related to the ISM Code should be introduced in formal education.



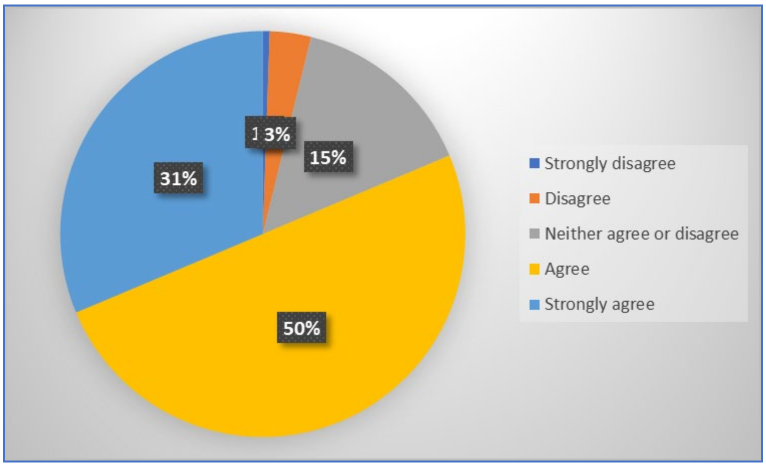
Graph 6 Distribution of students' opinions if it is necessary to implement an individual mandatory course in formal education

4. Did you participate at the individual mandatory course?



Graph 7 Distribution of students' participation in the individual mandatory course regarding the ISM Code

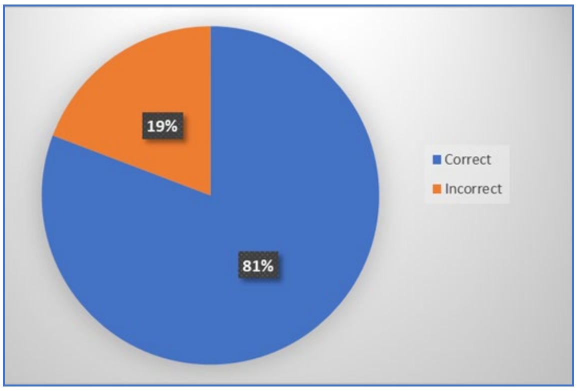
5. In my opinion, every seafarer should undergo a training course on the ISM Code before joining a ship.



Graph 8 Distribution of students' opinions on whether it's necessary that every seafarer should undergo a training course on the ISM Code before joining a ship

Questions related to general knowledge about the ISM Code (there is only one correct answer):

1. The ISM Code stands for?

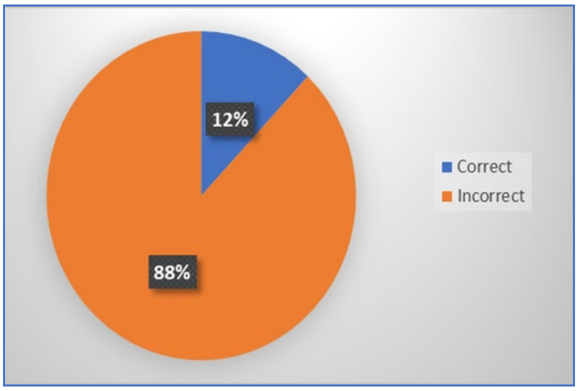


Graph 9 Distribution of students' answers

Predefined answers:

- International Safe Maritime Code
- International Safety Management Code
- Important Safe Operation Maritime Code
- International Supply Management

2. The ISM Code is an international standard for the safe operation of ships and the prevention.

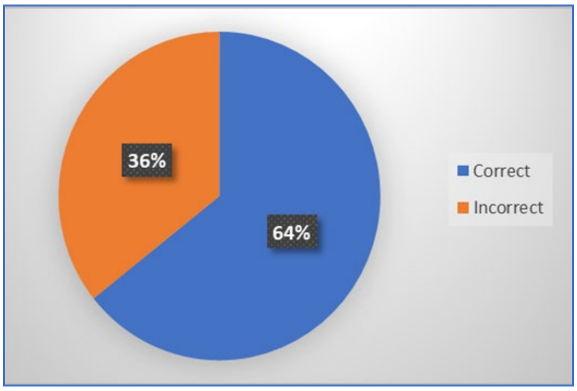


Graph 10 Distribution of students' answers

Predefined answers:

- Security
- Collision
- Pollution
- Accident

3. The purpose of the ISM Code is to?

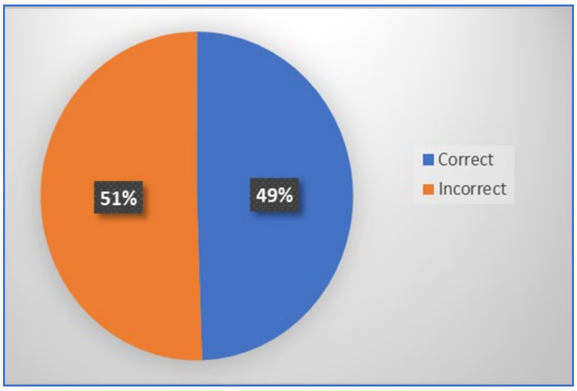


Graph 11 Distribution of students' answers

Predefined answers:

- Ensure safety and security at sea
- Prevent damage to the ship's equipment and cargo
- Prevent damage to the marine environment
- Ensure maritime security and prevent terrorist attacks on ships

4. Under the ISM Code, a company has to implement an SMS. SMS stands for?

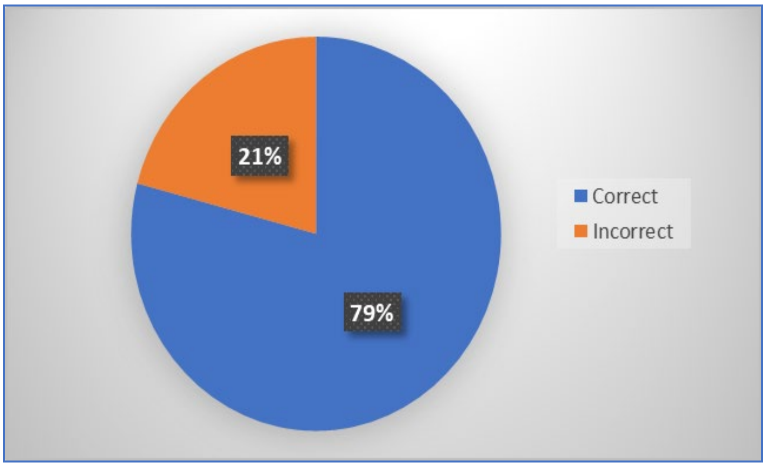


Graph 12 Distribution of students' answers

Predefined answers:

- Ship Management System
- Safe Maritime System
- Safety management System
- Service for Maritime Safety

5. Does the ISM Code apply to shipowners and ship operators?



Graph 13 Distribution of students' answers

The survey was conducted in paper form among the students during class, which enabled interaction between the respondents and thus ensured greater reliability and representativeness of the results.

4. DISCUSSION

The implementation of the ISM Code in the maritime industry has undoubtedly increased safety at sea, as evidenced by numerous researches [15] [16] [17]. The importance, understanding, and proper implementation of the ISM Code are crucial steps in preserving maritime safety. Therefore, it is necessary to properly analyze the survey results to create guidelines for a better understanding of the ISM Code.

It should be noted that the number of questions on knowledge of the ISM Code could be a limitation of the survey. Considering that the survey contained only five questions on general issues about the ISM Code, this may not have been sufficient to assess the actual knowledge of the students. In addition, the questions were general, making it difficult to form a judgement about possible deficiencies in knowledge of the ISM Code.

Analyzing the survey results, 66% of students consider that their knowledge of the ISM Code is poor or acceptable, which is a concerning finding. The stated percentage may indicate deficiencies in the current curriculum or insufficient practical application of the ISM Code during education. Although only 3% of students believe that they have not received sufficient information while even 64% believe they received sufficient information about the ISM Code, the fact is that 24% of respondents rate their knowledge as poor. Taking this into account, the question arises as to whether students are able to realistically assess the adequacy of the information they have received during formal education. Furthermore, the inconsistency between perceived knowledge and sufficiency of information received may reflect an extensive exposure to the topic or a lack of effective teaching methodologies.

A large percentage of students believe that an individual course related to the ISM Code should be included in formal education, as well as a mandatory course for every seafarer before joining a ship. These responses can be concluded that students understand the importance of the ISM Code or they acquired sufficient information and knowledge how ISM nowadays is important part of the safety in shipping.

Analyzing their knowledge of general questions related to the ISM Code, there was an overall accuracy rate of 57% correct answers. The highest level of knowledge was demonstrated by students of Nautical Studies academic programs. One of the contributing factors is the fact that the Nautical Studies curriculum provides more comprehensive coverage of the international safety standards associated with the ISM Code through a greater number of courses and hours in their study program related to safety of sea topics. In addition, it should be noted that when the more specific facts about the implementation of ISM Code have been asked, students answer show relatively high percentage of lack of knowledge. Namely, 51% of students answer wrongly on question what SMS stands for. This could lead to question of potential lack of educational methods or wrong perception of self-assessed knowledge.

5. CONCLUSION

Maintaining safety at sea is imperative for all stakeholders involved in the shipping industry. By introducing the ISM Code, the number of maritime accidents has significantly decreased, demonstrating its importance.

The research demonstrates that while the International Safety Management (ISM) Code has significantly improved maritime safety and reduced accidents caused by human factors, there remains a substantial gap in seafarers' understanding and knowledge of the Code. Due to improper implementation, understanding of ISM Code significance, or lack of knowledge among seafarers, there is still room for improvement in its application.

Despite mandatory implementation on board and in the shipping companies, formal education for seafarers on the ISM Code has not been established as a mandatory requirement. As the research has demonstrated, there is a lack of general knowledge regarding the ISM Code. Authors consider that introducing ISM Code as a mandatory course in formal education can enhance the understanding of the importance of the Code in the shipping industry. The survey results demonstrate that most students support the introduction of a mandatory ISM Code course in maritime education and advocate for compulsory ISM Code training before seafarers embark on their first voyage.

Given that human factor continues to be the leading cause of maritime accidents, and that lack of knowledge or improper implementation of the ISM Code is a recurring factor in such incidents, the study concludes that integrating a dedicated, mandatory ISM Code course into all maritime university programs is essential. This step would ensure that future seafarers, regardless of their specialization, possess the necessary understanding and competence to uphold safety standards and further reduce the risk of accidents at sea.

In light of the research findings, it is obvious that the curriculum needs to be improved. Although students recognise the importance of the ISM Code, the low accuracy of their responses and the fact that a large proportion of students rate their knowledge as poor, indicate the need for additional education to ensure the proper application of safety standards in practice. It should also be noted that the students have never been practically managed or operationally worked with the implemented ISM Code on board the ship, which inevitably reduces their perception of the importance of education and training related to the ISM Code.

Future research will investigate what size and complexity of the ISM Code related topics should be implemented during MET process but also more detailed questionnaire which could give more precise answer how the education methods and student learning process should be improved.

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PORT INFRASTRUCTURE AS A DETERMINANT OF CARGO HANDLING EFFICIENCY AND DEMURRAGE RISK

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Abstract

The condition and capacity of port infrastructure are key factors determining the efficiency of cargo handling operations and can directly influence the occurrence of demurrage. This study examines the impact of road infrastructure providing access to the port, the characteristics of the approach routes, the strategic positioning of berths, and the capacity of existing facilities. Their influence on vessel stay duration is assessed, along with the likelihood of demurrage charges arising from insufficient infrastructural support. Using data from a regional terminal, the analysis focuses on berth utilization patterns, the performance of portal cranes of varying specifications, and the effectiveness of supporting cargo-handling systems. Findings reveal that imbalances in infrastructure usage, limitations in access and operational zoning, and aging equipment can significantly extend vessel dwell time and increase the risk of demurrage. The study underscores the importance of coordinated infrastructure planning and targeted improvements to enhance port efficiency and mitigate operational delays.

Keywords: port infrastructure, handling capacity, cargo operations, demurrage, logistics efficiency

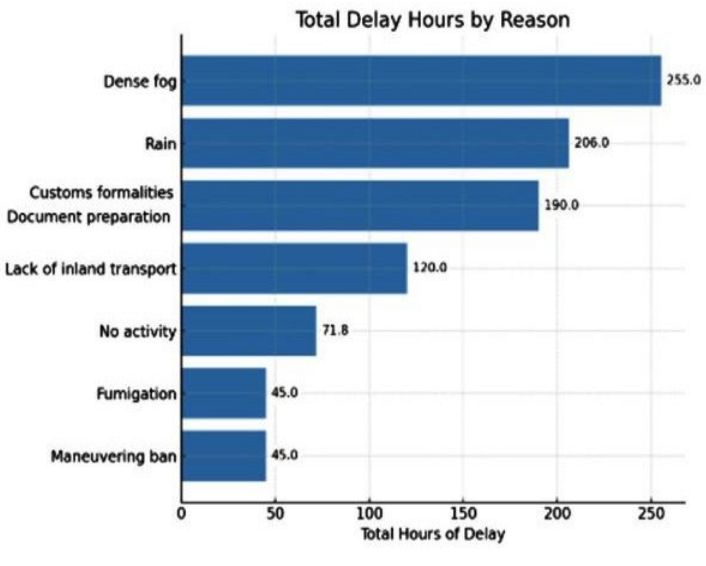
1. INTRODUCTION

In today's highly connected global economy, maritime transport is still the main method for moving goods in international trade, handling over 80% of the world's trade volume [1]. Seaports play a key role as logistical centers that help transfer cargo between sea and land transport. The way port operations perform greatly affect how efficient, cost-effective, and reliable the entire supply chain is. Delays in port activities, especially during cargo handling, can lead to serious disruptions and cause economic problems for everyone involved in maritime transport. One of the most important financial effects of these problems is demurrage. Although defined in contracts, demurrage often results from wider issues in planning and managing resources in the supply chain and in how port operations are carried out. From the point of view of shipping lines, charterers, and cargo owners, demurrage is seen as a cost that is unproductive and avoidable. Port infrastructure is a key factor in how fast and well vessels are handled. Good cargo operations rely on strong road links to inland areas, safe and easy-to-reach sea routes, well-located berths, and enough equipment and workers to handle cargo efficiently. When there is poor communication between these infrastructure elements, it directly increases the time vessels stay in port and raises the risk of demurrage. This is often clearly seen in small or specialized ports where infrastructure has not developed fast enough to match growing cargo volumes and changing logistical needs. An example of this can be found at a regional terminal located in Lake Varna. Although the port has a strategic role, it often experiences vessel delays that result in demurrage costs. This highlights the need for targeted upgrades and better management practices. This study aims to analyze how infrastructural factors influence vessel idle time and overall port operational efficiency and based on this to provide practical management to reduce demurrage risk.

The port consists of three berths, one of which is more frequently used due to its ability to accommodate larger vessels, thanks to its to ensure mooring to ships with bigger draughts. The quay features designated storage areas and are equipped with six portal cranes of various models and production years. Despite their age differences, all cranes comply with national standards and ensure reliable and efficient cargo handling. They are distributed along the berths and are individually numbered for identification. The busiest berth often operates multiple cranes simultaneously. In the event of a mechanical issue, a crane can be relocated as needed to maintain uninterrupted operations.

Each crane operates within a designated zone along the quay to avoid overlapping work areas and minimize delays. Supporting infrastructure, such as grain trays, is also in place to enable direct transfer of cargo from vessel to truck during unloading, further enhancing operational efficiency.

To assess port efficiency, average vessel dwell times from 2021 to 2023 were analyzed (Graph 1), encompassing both active cargo operations and idle periods. These durations reflect the impact of key factors on potential operational bottlenecks and the associated risk of demurrage.



Graph 1 Total Delay Hours by Reason

Source: Author's own elaboration using Python

2. METHODOLOGY

To explore the factors that influence cargo handling duration and the risk of demurrage at a bulk cargo terminal a multiple linear regression model is used. The model investigates how total vessel stay time is affected by the next operational factors: the type of cargo; the number of cranes used; the day of the week and weather conditions. The analytical process involves estimating regression coefficients, testing their statistical significance, checking residuals, and running simulations based on different scenarios. The regression model was built and applied in a standardized statistical software environment designed for multivariate analysis. The dataset includes 120 observations and was prepared by normalizing continuous variables, coding categorical data, and converting time-related information. This ensures consistency and helps to improve the clarity of the results.

After processing the results of the experiment and finding a relationship between the factors, the multiple regression analysis is used (1). It represents a quantitative assessment of the dependent variable Y = Idle hours (dependent variable representing total vessel idle time in hours).

$$Y=B0+b1X1+b2X2+b3X3+b4X4+b5X5+b12X1X2+b13X1X3+b14X1X4+b15X1X5+b23X2X3+b24X2X4+b25X2X5+b34X3X4+b35X3X35+b45X4X5+\mathcal{E} \quad (1)$$

Here:
X_1 = Day of the week (categorical variable indicating the operational day) X_2 = Berth (identifying the berth used for cargo handling)
X_3 = Number of cranes deployed X_4 = Cargo type (Grain, General)
X_5 = Reason: (Related delays - Maneuvering, Transport Issues, Weather, Cargo Issues) B0 = Intercept (baseline idle time when all predictors are at reference level or zero)
b1 to b5 = Regression coefficients indicating the marginal effect of each independent variable on idle time
$\mathcal{E}$ = Error term capturing unexplained variability

3. RESULTS

The model not only quantifies the direct effect of each factor on idle time but their interaction between them. This allows its ability to reflect real-world complexity in port operations. The results derived from these experiments allow identification of key contributors to inefficiencies of the port. Such it can be possible to undertake targeted interventions to reduce demurrage risk and optimize resource allocation.

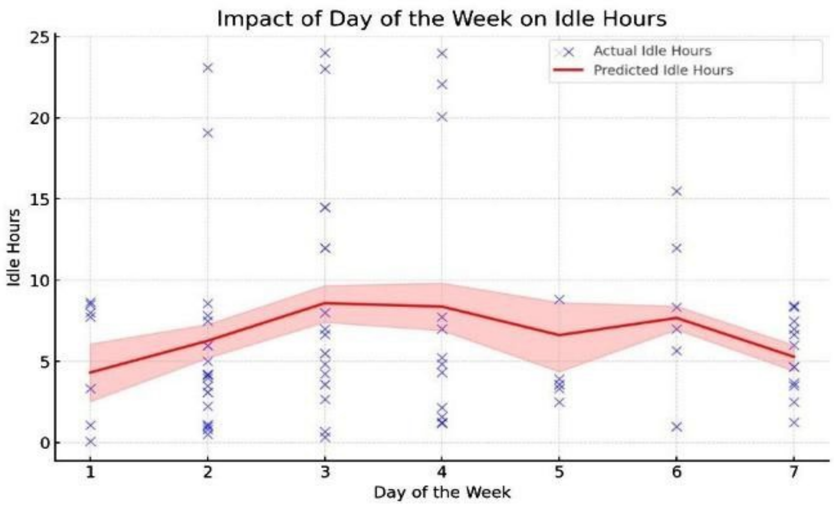
The regression analysis in this study was conducted using Python, a widely used language in scientific research, with the "statsmodels" library, which offers tools for statistical modeling and hypothesis testing. After the calculation and processing the results from the experiment, checking the significance of the members of the polynomial it ends (2) present of is:

$$Y=5.2277+0.3589X_1+1.6671X_2-2.1605X_3+1.4468X_4+3.7950X5+\mathcal{E} \quad (2)$$

The analysis reveals several statistically significant operational factors affecting vessel idle time. Notably, the number of cranes deployed shows a strong association with reduced idle time, indicating that increasing cargo-handling capacity generally helps lower vessel waiting periods. Specifically, deploying more than three cranes is associated with an approximate 20% decrease in idle time, demonstrating the clear operational advantage of enhanced handling resources under favorable conditions. Conversely, delays caused by vessel maneuvering and inland transport limitations significantly increase idle time, underscoring the impact of logistical constraints on port efficiency. As a result of observation, interaction effects between crane deployment and certain operational delays were identified, suggesting that the positive effect of additional cranes can be diminished when simultaneous bottlenecks occur in other parts of the logistics chain.

Most predictors in the regression model are statistically significant at the 5% level ($p < 0.05$), confirming the reliability of these findings. Overall, the results highlight that while increasing crane capacity generally improves vessel turnaround efficiency, this benefit is contingent upon the resolution of other operational delays.

The study confirms that the day of the week has a statistically significant influence on idle time. The results indicate that idle time tends to be lower at the beginning (Monday and Tuesday) and end (Friday to Sunday) of the week, with a pronounced rise on Wednesday and Thursday.

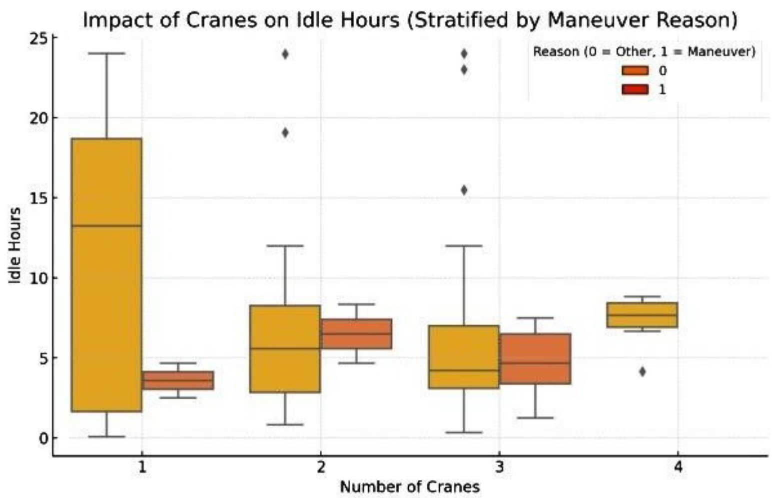


Graph 2 Impact of Day of the Week on Idle Hours

Source: Author's own elaboration using Python

The day of the week has a significant impact on idle time. This is mainly due to organizational and operational factors related to how busy the port is on different days. Shorter idle times at the beginning and end of the week may result from better planning or lower activity levels during those periods. The findings highlight the need to improve operations on days with higher idle time, such as Wednesday and Thursday. This can be done through better resource allocation and more effective scheduling of activities. Additionally, further analysis of the reasons behind the variations on these days could lead to useful recommendations for reducing idle time.

To better understand how port operations can be improved, this analysis looks at the link between the number of active cranes and vessel idle time. The data is grouped by the type of delay, with a focus on whether the cause was related to crane maneuvering or to other operational factors.



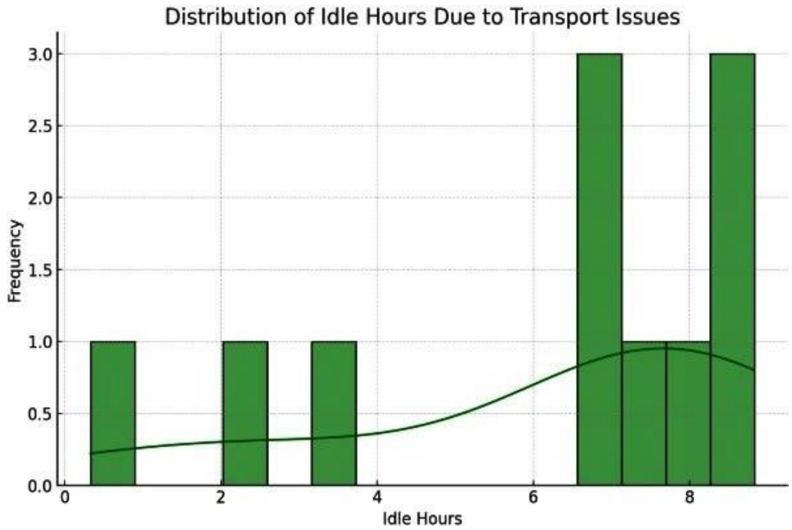
Graph 3 Impact of Cranes on Idle Hours (Stratified by Maneuver Reason)

Source: Author's own elaboration using Python

This method helps assess how both equipment availability and the type of delay affect overall port performance. When only one crane is used, idle times vary widely, especially for delays not related to vessel maneuvering. In these cases, the median idle time is high, and extreme values can reach up to 20 hours. This suggests that using a single crane is often not enough, particularly during complex operations, leading to long periods when no activity occurs. Adding a second crane leads to a clear improvement. Idle times become more consistent, and the median drops significantly. The difference in idle time between maneuver-related and other delays also becomes smaller. This indicates that even a small increase in crane numbers can ease congestion and improve efficiency across different types of interruptions. Deploying three cranes further improves performance. Idle times are tightly grouped, the median continues to fall, and very few outliers appear. This points to a more reliable and efficient system, where extra cranes help reduce delays and raise handling capacity. At four cranes, idle times are the shortest and most consistent across all delay types. The gap between maneuver-related and other delays becomes minimal. This suggests that using four cranes may be close to the ideal setup, balancing resource use with operational efficiency—even during more complex handling tasks.

In summary, the number of cranes in use plays a major role in port efficiency. The biggest improvements happen when increasing from one to three cranes, with smaller gains beyond that. While delays linked to vessel maneuvering tend to be slightly longer, this effect lessens as more cranes are added, showing how important proper equipment levels are for keeping operations smooth and reducing downtime.

Following the analysis of crane deployment and its effect on idle times, it is important to examine another critical factor influencing port efficiency - transport-related delays. The horizontal axis in the chart represents idle time (in hours), while the vertical axis shows how often each idle time duration occurs. The data reveals that most transport-related delays lead to relatively short periods of inactivity. However, there are clear peaks at six and eight hours, indicating that certain delay durations occur more frequently than others.



Graph 4 Distribution of Idle Hours Due to Transport Issues

Source: Author's own elaboration using Python

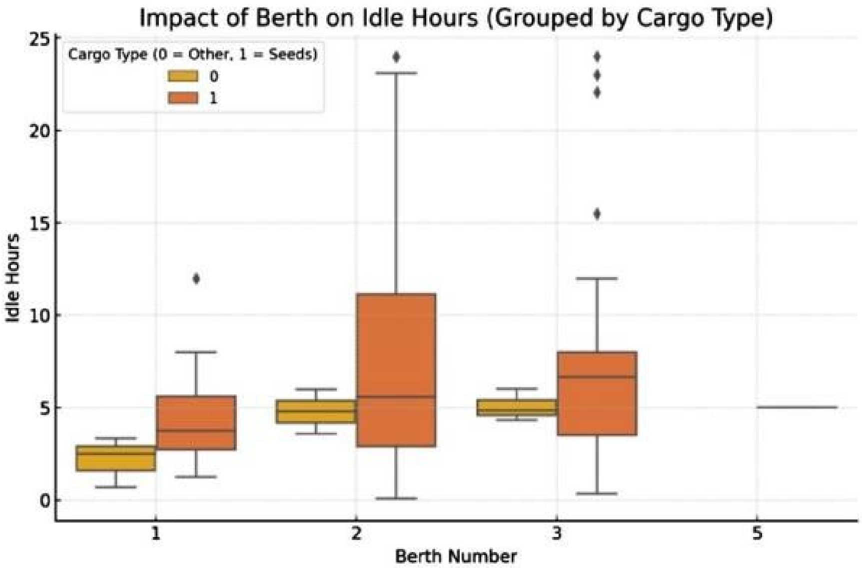
These peaks suggest that transport delays often result from recurring inefficiencies in the inland logistics chain. Common causes may include poor coordination between logistics teams, delays in vehicle scheduling, or broader system bottlenecks. The overall trend shows that idle times tend to rise in frequency within the mid-range (6–8 hours), before gradually decreasing for longer delays. This indicates that while serious transport disruptions are less frequent, most delays are of moderate duration and occur in a consistent pattern. The main takeaway from this analysis is that transport-related issues are a significant and largely predictable source of idle time. Improving communication, scheduling, and the allocation of transport resources can help reduce these delays. By targeting these areas, ports can achieve better efficiency and minimize the operational impact of transport disruptions. Building on the issue of transport-related delays, a key infrastructural factor contributing to inefficiencies is the poor condition of the road network connecting the port to inland transport routes. A key limitation identified is the poor quality and design of the main access roads, which are heavily used by trucks transporting cargo to and from the port. These roads pass through industrial areas and rely on secondary routes that suffer from narrow widths and damaged pavement. In many sections, the road width is effectively reduced to about 1.5 lanes, making two-way traffic difficult. Often, one truck must stop to let another pass, leading to delays and traffic bottlenecks.

Figure 5 Narrow Road Limitation

Source: Author's own elaboration based on Google Earth imagery

These road constraints limit the smooth flow of cargo and increase the chances of congestion and service delays. As a result, they pose a significant risk for demurrage and contribute to broader logistical inefficiencies.

The evaluation in Graph 6 explores how berth location affects vessel idle time, with results separated by cargo type classified broadly as "grain" and "other cargo." The data provides insight into how idle time changes across different berths and how the type of cargo influences operational efficiency.



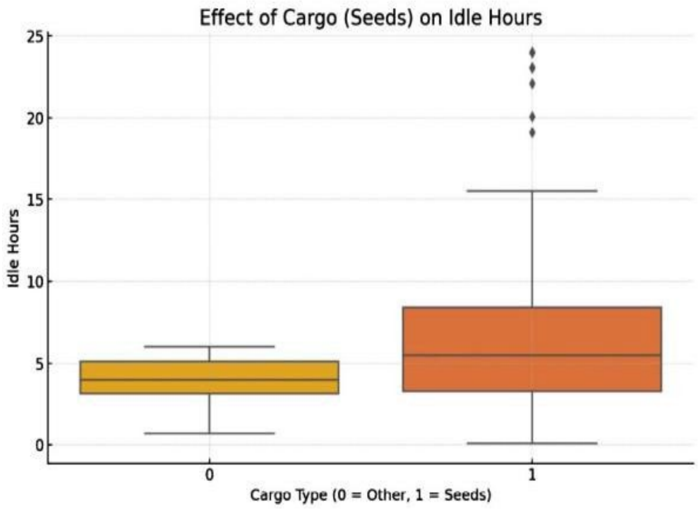
Graph 6 Impact on Berth on Idle Hours (Grouped by Cargo Type)

Source: Author's own elaboration using Python

At Berth 1, idle times for both cargo types are tightly grouped and close to the median. However, grain cargo shows a slightly higher median and more variation than other cargo. This may indicate that handling grain commodities at this berth takes more time or is more sensitive to operational challenges. Berth 2 shows a much larger difference. Grain cargo has a wider range of idle times, with a higher median and many outliers. This suggests that grain handling at this berth is more likely to face delays, possibly due to irregular processes or system-related issues. In contrast, the other cargo at Berth 2 has shorter and more consistent idle times, showing a more stable operation. At Berth 3, grain cargo again shows higher variation in idle times, though the difference between the two cargo types is smaller than at Berth 2. This could reflect more consistent handling procedures or better use of resources for grain cargo at this berth. Other cargo continues to show low idle times with little variability.

Overall, Berth 1 appears to be the most efficient, with low idle times and minimal differences across cargo types. The narrow distribution and lack of outliers suggest smooth operations and effective use of equipment. The results point to Berths 2 and 3 as areas needing improvement, especially for grain cargo, which repeatedly shows longer idle times and higher variability. These delays may be linked to the more complex nature of grain handling or resource limitations, such as fewer cranes or less organized work areas. Additionally, cranes labeled as units 1 and 5 perform better, showing lower idle times. Their efficient operations could be used as a model to improve performance at other berths by adopting similar practices and optimizing the allocation of handling equipment.

For grain cargo a higher median idle time is observed, along with greater variability in the data. The presence of outliers in this category indicates that, in some cases, the idle time during grain handling can be significantly longer compared to other types of cargo. These longer idle times may be caused by specific handling requirements for grain, such as the need for additional inspections, controls, or other administrative procedures.



Graph 7 Effect of Cargo (grain) on Idle Hours

Source: Author's own elaboration using Python

This review confirms that the type of cargo is an important factor influencing idle time. Due to its particular characteristics, grain handling tends to result in longer periods of inactivity compared to other goods.

4. CONCLUSION

This study has examined the key operational factors influencing vessel idle time within port terminals, drawing on regression-based analysis and supporting descriptive insights. The findings demonstrate that idle time is not random but strongly shaped by a set of identifiable and measurable variables. Specifically, the analysis identified five main predictors: day of the week, berth assignment, crane availability, reason for delay, and cargo type. These factors collectively offer a practical basis for improving port efficiency and reducing demurrage risks. Crane deployment emerged as one of the most influential variables, with results confirming that increasing the number of cranes significantly lowers idle time. This highlights the value of strategic equipment allocation to boost terminal performance. Berth assignment was also found to correlate with idle time, indicating that certain berths may be prone to delays due to structural layout or resource constraints. Transport-related delays were shown to contribute measurably to inefficiency, adding approximately 1.45 hours to vessel idle time on average. These delays often stem from predictable issues such as poor road access, inadequate coordination in inland logistics, and scheduling mismatches, underscoring the need for more integrated transport planning. The analysis also revealed that cargo type, particularly bulk commodities like grain, tends to require longer handling times and may demand specialized equipment or procedures, adding further complexity to terminal operations.

In light of these findings, the study proposes a combination of infrastructure enhancements, operational adjustments, and technological integration to mitigate the identified inefficiencies - such as improving crane deployment strategies, optimizing berth usage, addressing transport bottlenecks, and tailoring handling approaches to cargo characteristics. Enhancing these areas through coordinated planning and investment can substantially improve port efficiency, reduce idle time, and minimize the likelihood of demurrage.

Priority should be given to modernizing berth equipment, especially mobile cranes with larger grab capacities, to enhance cargo handling capacity and minimize delays under varying conditions. Complementing this, targeted workforce training programs are essential to ensure effective use of equipment and sustain productivity over time. Significant attention must also be directed toward upgrading the road network that links the port to inland transport routes. Current access roads are narrow, degraded, and unsuited for heavy traffic, creating frequent bottlenecks and contributing to transport-related delays. Widening these routes and improving surface conditions would support smoother cargo flow and reduce demurrage risk. Operationally, adopting adaptive scheduling based on peak traffic and cargo type can reduce inefficiencies, while expanding crane availability and maneuvering areas will directly impact turnaround times. The integration of automated monitoring systems and simulation models is also recommended to support real-time decision-making, predictive maintenance, and long-term planning.

Together, these measures provide a practical and forward-looking framework for developing a more resilient, efficient, and competitive port system.

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IMPLEMENTATION OF ARTIFICIAL INTELLIGENCE IN THE RAILWAY TRANSPORT AND ITS EFFECT ON PORT EFFICIENCY

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Abstract

With the latest advancements in the field of Artificial Intelligence there could be a significant increase in the efficiency of different parts of the transport system. The purpose of the current paper is to analyse the weak points of the railway transport, where artificial intelligence is suitable for implementation, as well as the current limitations of the AI technology. We are going to analyse the available data on transport operators, who have already implemented Artificial intelligence into their transport systems, as well as the thoughts and opinions of those who plan to implement AI in their transport operations in the near future. The main goal of this current publication is to summarize strong and weak points of artificial intelligence which can be implemented in the railway transport system, and the possible effects it can have on port efficiency.

Keywords: types of artificial intelligence, transport system, railway transport, port efficiency

1. INTRODUCTION

Artificial Intelligence is technology field which is rapidly developing in the recent years. More and more aspects of daily life incorporate the use of computers and different forms of computer helpers. With the recent advances of the technology, it is logical to turn our attention to the improvement of the commercial transport.

As an emerging field of research, the topic of AI has been subject to a considerable number of publications, including, but not limited the following topics:[4]

- Definitions of the term "Artificial Intelligence"
- Types of AI
- AI in everyday life
- AI in production
- AI in the transport system
- AI in the education system
- AI as a management tool
- Future of AI
- Variations and combinations of the above-mentioned topics

This list is by no means complete, as theoretical and practical advances are made at increasing rates in the recent years.

As the AI technology is further perfected, more ideas for its implementation emerge, including integrating AI in the world transport system. For this paper can be considered complete, a comparison is made between the main benefits and challenges of introducing Artificial Intelligence in the different types of transport. As this is a first step in a series of publications by the authors, the main focus is on the implementation of AI in the railway system, with the task of providing a short and concise overview of the current trends and achievements regarding the topic.

The world transport system consists of the 5 main types: road transport, railway transport, water transport, air transport and pipeline transport.

Although some authors do not consider pipeline transport as one of the major means of transport by itself, it is a part of the transport system that can benefit from the new technological advancements in improving efficiency and reliability.

Each of the main types of transport poses weak areas and present unique challenges in terms of optimizing transport routes, decreasing delivery times, increasing reliability, as well as lowering costs.

First it is necessary to define what the term "Artificial Intelligence" means in the context of this current paper. Artificial Intelligence (AI) is defined as the ability of a computer system to perform tasks which are typically associated with human intelligence, which may involve, but not limited to, learning, reasoning, problem-solving, perception, and decision-making. This if usually achieved by complicated computer algorithms and other techniques for achieving a predefined goal. [6][8]

2. TYPES OF ARTIFICIAL INTELLIGENCE

Depending on task at hand there are several subtypes of AI. Most current examples of AI use a type of "Artificial neural network", that can be described as collection of artificial nodes that mimic the composition and function of a human brain. The system is then trained on large amounts of data, so that patterns are formed and dependencies can be found in fresh set of information. An interesting side effect of this method is that sometimes there are connections between parts of the data set, that are correctly recognized by the neural network, but were previously unknown to the researchers doing the particular experiment.

2.1. GPT AI

The most common type of AI are the Generative pre-trained transformers (GPT) which are Large Language Models (LLMs) working on the principle of text prediction and logical weights of words in the context of given sentence task. As previously stated, they use large amounts of text materials to make the initial training on a given subject.

This type of AI is suitable of optimisation and prediction of parameters in a given data set of pretrained data, which is why it is a great idea generator and analyst of information, which otherwise be a huge expense of time and resources, if the same task was performed by human employees.

2.2. Generative AI

Generative Artificial Intelligence (Generative AI, GenAI, or GAI) is another subtype of AI, that uses initial training data in the form of text, images, video and other form of information, but in contrast to GPT the main task is to produce new data, based on the corelations in the initial data set.

The main focus of this type of AI is to generate new solutions to existing problems, and not so much on analysing and optimising a set of input data. A few initial applications of this type of intelligence are the creation of new pictures, text-to-speech and more recently creation of short videos with increasing accuracy.

2.3. AI agents

AI agent is a software that has access to environmental sensors, is capable of making autonomous based on the current readings, and take appropriate action to achieve specific goals. The agents are capable of interacting with users or even other AI agents. AI agents usually have limited capabilities, depending on the hardware used, the amount of training data and time constraints for the decision making. AI agents incorporate usually incorporate learning algorithms, which improve their performance with time of use or additional training.

2.4. Levels of AI

The are three kinds of AI based on capabilities:

- Artificial Narrow Intelligence, also known as Weak AI, is a type of AI that is trained to perform a single or narrow task, usually faster and more precise than a human. This is the only currently available kind of AI and is greatly limited to its initial programming and lacks the ability to learn new tasks without human input
- Artificial General Intelligence (AGI), also known as Strong AI, is only theoretical concept. AGI is the advanced version of Narrow AI and can make decision based on previous experience without human intervention, as well as acquire new skills. This is the equivalent of human intelligence.
- Super AI is commonly referred to as Artificial Superintelligence (ASI). This is an evolution of AI beyond human understanding and is the equivalent of human consciousness. This type of AI will be capable of experiencing emotions, have needs, and can even possess beliefs and desires of their own. This form of AI as well as AGI is still theoretical [5]

2.5. AI Limitations

It is important to note that as helpful as this type of AI models seem, there are some considerable limitations [3]:

- The AI is limited to the size of the initial data set it was trained for.

When insufficient data is available to the language model, there are well documented cases of so called “hallucinations” of the AI. This is represented by a seemingly believable response of the model, but in reality, the outputted data is complete made up by the neural network, as that is the nature of predictive responses

- Limitations of available system resources including, in some cases, ones caused by the physical size of the AI system, budget related constraints during the initial setup, as well as scope and complexity of tasks performed by the AI, requiring more expensive operating setups and configurations

  Limitations in this category directly affect the performance and capabilities of the deployed AI system

- The cost of initial training and physical infrastructure needed for the function of this type of AI is considerable

Research shows that it is of the great importance that the data used to train AI models should be original data and not the so called “Synthetic data”, produced by other language models, which could lead to data corruption of the database, producing over time, increase of nonsense output results. [3]

The same data limitations apply also to the training of the other subtypes of AI. The initial training data should be carefully selected and verified.

- Security of access to the operating system and core database. While linking different parts of the transport cycle in a unified control system can be beneficial increasing efficiency, this introduces a single point of failure, where an outside attacker can disrupt the normal operations of the system, and in some cases cause physical damage to the infrastructure, as well as injury to passengers and service staff.

On that note some, restrictions should be put in place, as to what extent the AI is able to incorporate user input in its continued training, to prevent unintentional, or in some cases, malicious introduction of conflicting data, altering the initial data set.

2.6. The correct AI for the correct task

As there are many types of AI systems, it is important to select a suitable AI for the task at hand. Similarly to any other specialised equipment, one with a narrow application toward a specific goal would naturally produce better results. Some important factors that need to be considered are budget constraints, the necessary accuracy during the performance of the task, the size of the database that would be required for the task, as well as what will be the safety concerns, in the cases of output errors, arising from the use of the AI.

There are 2 possible scenarios that should be avoided, that would produce similar undesirable results:

- Deploying a system with insufficient resources for the desired task, causing an overwrite of the initial conditions and variables inputted at the beginning of the task due to exhaustion of system memory, as a large task progresses over time. This usually results in loss of train of thought of the AI and the above mentioned "hallucinations" of the computer system, creating random outputs and solutions that seems logical, but completely untrue considering the initial definition and parameters of the task
- A system with sufficient system resources for the initial single task it was designed for, used for multiple significant tasks competing for resources or allowing too many users with simple tasks, leading to the same resource exhaustion and corruption of the primary functions of the AI model

Both scenarios describe decisions to use an AI system in a way it was not initially designed for, which can have serious consequences depending on the levels of trust in the outputs and suggestions of the AI system.

Unfortunately, this is true for any new technology that is implemented and over-trust in the system in some cases can be fatal. Examples in recent years would be the numerous accidents with modern cars in Autonomous Autopilot mode failing to recognise danger on the road, as the initial data used to train the AI did not contain obstacles of that particular kind.

The main conclusion here, as with any tool and technology, is for the AI to be operated in a way that was intended by the manufacturer and any rules for its use that were given to ensure safe and efficient operation.

3. AI IN THE RAILWAY SYSTEM

One major part of the global transport of goods is done through railway transport. As such an integral part of the world's transportation, it is a main focus of research, and any optimizations that can be made, will have great impact on the speed and reliability of the whole multimodal transport system.

The railway systems are a collection of subsystems each of which can be assisted by additional automation. There are different areas where AI can be applied with different levels of success.

3.1. Predictive Maintenance

AI can be used to analyse data from sensors onboard trains and tracks to predict equipment failures before they happen. There are currently field tests of AI assisted systems where pictures of found defects on tracks are fed to an analytical algorithm, to mark areas in need of repair or additional verification by workers onsite. Combined with live sensors on board trains, the system can make live predictions about the condition of each train composition and the probability of defects. [1]

This can greatly reduce downtime, lower maintenance costs, and prevents accidents.

3.2. Traffic Management and Scheduling

AI can be used to help optimize train schedules and manage traffic flow in real-time. By combining patterns form previous periods and the data input about the position and speed of each train composition, the system can adjust the speeds of each train so there are no delays, caused by manoeuvring in the area. This will reduce delays, improves punctuality, and maximizes track utilization.

3.3. Safety and Surveillance

AI can be used to alert the train driver and the traffic control about any obstacles and anomalies on the train tracks and if necessary, take control to avoid collision. This is the equivalent of computer sensors in modern cars.

This system can be used to prevents accidents, enhances passenger security, and detects trespassing or obstructions.

Part of this system Is the use of drones to survey the railroad tracks in search for defects and anomalies. Here AI models can be used to analyse pictures and videos of the tracks, and using machine learning to detect areas that need to be repaired or to be scheduled for future maintenance.

3.4. Autonomous Trains

The AI system can be used for self-driving train compositions, supervised by and operator in an office

The system Improves efficiency and consistency, especially in urban metro systems with examples being cities like Paris, Dubai, Tokyo. [9]

3.5. Energy Optimization

AI can be used to optimize acceleration, braking, and speed to reduce energy consumption by taking in to account multiple sensor readings about the local conditions of the railway, in combination with the traffic control system, precise movement of the terrain compositions can be achieved, so as there are minimal delays, decrease in operational costs and environmental impact.

3.6. General thoughts on AI in railway transport

For AI to be successfully implemented some basic conditions need to be met. The AI system has to have access to the live data about the current condition of the railway system. The task assigned to the system has to be precisely defined and for the moment human additional control cannot be avoided. The type of AI has to be of the AI Agent type, so as to be able to interact with the controls for the railway system, but the decisions must be preprogramed. In case of conflict between data and preprogramed commands it has to be able to contact the operator on duty.

4. AI IN OTHER MODES OF TRANSPORT

Similarly, AI can be implemented with varying success in the other parts of the world's transport system. Depending on the specifics some are more suitable to be equipped with AI than others.

4.1. AI in the road transport

Road transport is one of the oldest modes of transport and as such most new technologies are first tested and implemented here. An example would be the standard inclusion of a rear-view parking camera in most new trucks and cars as an assistance tool. Logically the next step is the use of front cameras and sensors that can be combined with smart AI assistance systems. The functions and reliability differ greatly between manufacturers.

Diagnostic sensors have been part of design of most modern vehicles as early as the 2000s. Modern cars and trucks already have the necessary equipment with the ability to be monitored remotely. This can easily be combined with a Predictive Maintenance AI, monitoring the whole company fleet, advising the optimal maintenance intervals and minimising downtime for repairs. The only necessary addition is a reliable cell tower-based telemetry system to enable the real-time transmission of data to the AI control centres.

Traffic Management and Scheduling is more difficult to be achieved, compared to the railway system as there are vastly more parameters that have to be controlled and monitored. The solution is the replacement of the greater part of road vehicles with autonomous ones, including passenger traffic for the AI system to be fully applicable.

On account of scheduling, AI can make analysis and predictions for the optimal times to send the transports, depending on the road conditions, including intensity of current traffic, reports of accidents on route, and the exact moment the next delivery will be needed, if it is part of a predictable production cycle.

Safety and Surveillance AI is already implemented in most modern cars and trucks, including accident-avoidance systems, automated speed and distance systems, as well as live video feeds for the vehicles transporting valuable goods, especially financial and military transports. The innovation here will be centralizing all that information can be handled by an automated system, that can be combined with Resource Management AI to optimize delivery times in a production process.

Autonomous Road Transport, as stated above, is harder to be implemented in comparison to the railway transport, by the simple fact that it would be far easier to replace most, if not all, trains so as all the traffic can be centrally controlled and managed by AI, compared to the road system where there are considerably more human driven vehicles and hazards on the road.

As described in the Traffic Management section, an Autonomous transport system can only be optimal if the transport vehicles are all AI controlled and coordinated. The combination of human operated and AI controlled transport introduces variables and situations that can prove fatal, as more training for the recognition systems and testing is needed.

4.2. AI in the water transport

Water transport presents unique challenges while implementing AI based systems. The main difference is that during the most international voyages, ships are in the open seas, where live telemetry is hard to be transmitted, and the only available communication is the satellite based one.

While in recent years there has been significant progress in achieving better coverage, with the regular launches of new communication satellites, there are still many "blind spots". As such many of the control systems on ships are still monitored and controlled by human crews. Because of this the use of Predictive Maintenance AI is very limited.

On the other hand, Traffic Management and Scheduling AI can be applicable as ship traffic by its nature is slow and predictable. AI systems can be of great help to traffic control in busy ports, while not directly controlling the involved ships.

While the use of Autonomous Ships is still very limited, there are 4 main categories of autonomy which are in varying development stages by different countries [7]:

- **Remote control:** An operator controls ship operations remotely without the use of an AI system, and minimal crew on board
- **Decision support:** Copilot or an AI decision support system that operates locally on the ship and is connected to the ships sensors, suggesting the optimal course of action in the current situation.
- **Supervised autonomy:** Similar to the Decision support system, but with the distinction that it is capable of making autonomous decisions while supervised by operators

- **Full autonomy:** The advanced version of Supervised autonomy system, where the operator takes control of the vessel only in emergency situations

4.3. AI in the air transport

Out of the major types of transport, air transport presents most challenges in fully implementing AI systems. By its nature air transport Is must susceptible to input errors and as such the potential for damages that can be inflicted is the greatest of all the modes of transport.

Air transport is characterised by its complex and fast paced control systems, that can benefit from artificial intelligence, but on the other hand the margin for error is the smallest.

While pilots can benefit from additional decision support systems, currently there is no replacement for the crews training and experience. This can be combined with a Safety and Surveillance AI, as similar, but less functional systems have already been implemented for accident avoidance.

The most readily applicable system is the Predictive Maintenance AI, while the inspection and maintenance standards are much higher, compared to other modes of transport.

Traffic Management and Scheduling AI here can be implemented most successfully, compared to other modes of transport, with the clarification that it should be focused on assisting traffic control tower of the airports where the workload and speed of decision making is critical, and not so much as a tool for optimizing the transport flow of an air transport operator, which is another possible use.

Most situations in the aviation are unique, which makes difficult a universal training data set to be constructed, so that an autonomous AI system can be reliable. As such with the current level of the AI technology Fully Autonomous cargo planes are not expected to be widely available in the near future.

4.4. AI in the pipeline transport

The pipeline transport is the simplest of the main types of transport, as it does not use moving vehicles. However, this area of transport can benefit from advancements, similar to the railroad system. The combination of drones and AI models with machine learning can be extremely beneficial in finding defects in long overground pipelines, long before they suffer critical structural failure.

5. RAILROAD TRANSPORT AND PORT EFFICIENCY

Railroad transport is one of the main sources of cargo in any port. As the definition of port efficiency is essentially the speed and quality of the act of transferring goods form one mode to another. This means if there are delays in the in-bound and out-bound trains the overall port efficiency will suffer.

Port efficiency is dependent on combination of multiple external and internal factors, a significant part of which is the performance of different parts of the intermodal transport system. [2]

The potential increase in efficiency and reliability of the railroad system can contribute to maintaining a steady flow of cargo to the port, and in combination with port-side implemented AI solutions, a unified system can be constructed, leading to decreased delays and more accurate planning of traffic and deliveries.

Railroad transport share varies in different parts of the world transport system, and as such it would be difficult to calculate the overall impact of implementing AI systems. As some regions are still developing, while others are in desperate need of renovation, as well as the aging (and in some places missing) infrastructure are major obstacles in attaining higher efficiency. While using modern technological solutions is encouraged, without a solid and reliable railroad system the proposed advantages can be greatly diminished. This is why the first logical would be the use of AI systems to detect flaws in the current infrastructure and accelerate the modernisation and improvement of the external to the ports transport system, and only then the actual significance of implementing Artificial intelligence in port operations can be measured.

With the increase of restrictions regarding a more efficient and eco-friendly transport system, introducing AI can be beneficial in lowering energy consumption and proving to be a valuable tool in the management of the intermodal transport involved. The improved communication and integration in a centralised system will make possible for the traffic and rate of delivery to be optimised, avoiding congestion and large delays, resulting in higher efficiency, and more economic and technical results.

6. CONCLUSION

AI is an emerging technology that can be used to assist in many aspects of production and the worlds transport system. With the advancements in Artificial Intelligence, systems become more precise and optimised, leading to economy of power, resources, delivery times, as well as the overall safety and reliably are greatly increased.

The possibility of integrating AI in the world transport system greatly vary depending on the type of transport and state of the existing infrastructure.

The main challenges in implementing Artificial Intelligence are the cost of initial investments and some of the current limitations of the technology. With the development of more complex and efficient AI, the technology can be more easily integrated in the control and operation of a fleet of vehicles and vessels.

Security issues are a topic of research, ranging from external influence from attackers, with the idea of a centralised control system to improve efficiency and coordination, to accidental corruption of the database, caused by a combination of continued machine learning and improper use and inputs by operators.

By selecting the proper AI for the task at hand there can be great benefits to the efficiency of the worlds transport system.

Based on the information collected for the current research, the use of **AI in the railway system** shows most promise for rapid development, considering the complexity of the control systems involved and the possible areas of Improvement, at the current level of the technology. By implementing AI in the railway system there can be a great reduction of downtime, lowering of maintenance costs, prevent accidents, as well as improved coordination and reduction in delays.

AI in the road transport system is also a hot topic of research, with the current implementation of safety and accident-avoidance systems present in most modern cars and trucks. One of the main obstacles for achieving optimal efficiency here is the unpredictable behaviour of human operated vehicles.

AI in the water transport system is harder to implement compared to other modes of transport, as there are difficulties in the communication and transmission of live telemetry when ships are far from shore-based data infrastructure. There are however, decision support systems that are much easier to be integrated, considering the slow speed of events and results of actions taken, while controlling a vessel.

AI in the air transport system is the hardest to implement, in regard to autonomous control of planes, but it can be a valuable tool at traffic control towers, where the work load is high and fast and precise decisions have to be made.

There are many papers that have been written on the topic of implementing AI in the railroad system, but most focus on describing the positives in the selected area of research. It is much harder predict what the overall result will be by combining all the purposed ideas and solutions at the same time, provided the current limitations of the AI technology are overcome. [3][4]

While major advances in AI systems, as well as their possible implementations, are relatively new, technologies and solution are constantly emerging. This means we are yet to see what the financial and technological impact will be on the world transport system, as well as the change in efficiency of railway and port operations in particular.

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EFFECT OF INTRODUCING ARTIFICIAL INTELLIGENCE IN LOGISTIC SYSTEMS AND PROCESSES, POSSIBILITIES FOR DEVELOPMENT AND IMPROVEMENT

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Abstract

Nowadays, when we talk about modern systems, it is almost impossible not to consider introducing artificial intelligence into any process in order to facilitate and improve it. Logistics, being a highly complex matter, involving different systems and chains of supply, makes no difference. Our paper aims at pinpointing those aspects of artificial intelligence which may be the most beneficial for the improvement of logistic systems. We are going to analyse data regarding practitioners' opinion, ones who have already implemented Artificial intelligence into their systems as well as those who are planning to include it into their processes into near future. Our main goal is to summarize strong and weak points of artificial intelligence in logistics, possible development and evolution. Without claiming to be experts in artificial intelligence development and code, we are analysing it more as professional users rather than developers.

Keywords: artificial intelligence, logistics, development, analysis

1. INTRODUCTION

The modern world is witnessing a real technological revolution. The development of artificial intelligence has been a goal in the evolution of computer science since the 30s and 40s of the 20th century. As a result of multiple efforts and technological advances, the first multitasking AI software, created by Open AI was introduced to the world in early 2020s. It created a wave of reactions, varying from extreme enthusiasm to fear and even prophecies that the end of the world has arrived. Over the years, it has proven itself to be an extremely useful tool and has begun to find its place in many aspects of peoples' lives. As a result, nowadays more and more specific tools are emerging to boost many areal of social and economic life. The use of artificial intelligence (AI) is becoming more and more important, saves significant amount of time and eventually makes work productivity of those capable of using it wisely, remarkably higher. It is probably the first technology which, by being able to self-teach itself, follows its own evolutional path, similar to the one a new specialist would follow when entering a certain professional field of expertise. However, like every technology, especially in its infancy, AI has some limitations and understanding them is crucial for the proper development of both technology and users.

It is no surprise that AI finds its way in almost every aspect of human endeavours and logistics and supply chain make no exception. The ability of AI to provide fast data analysis, monitor multiple processes simultaneously and makes reliable forecasts makes it one of the most useful tools in hand for a logistics expert.

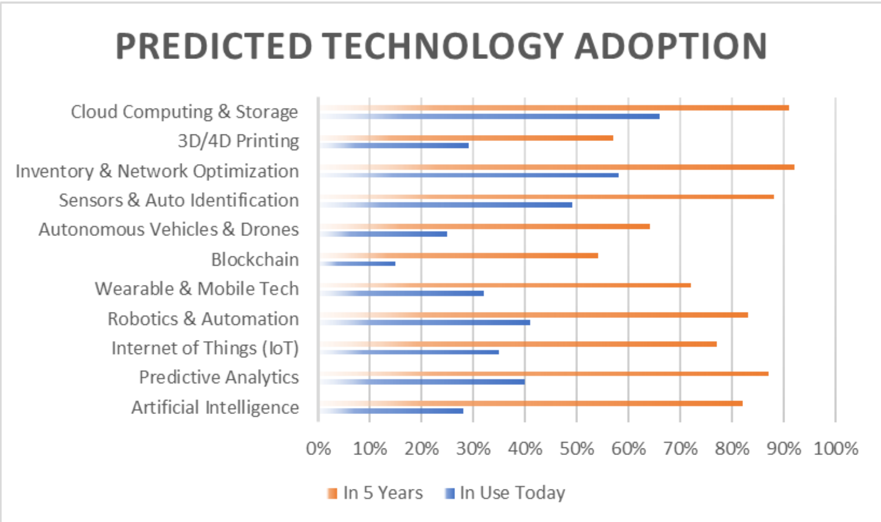
But one must be aware of the weak aspects of AI, its tendency to "dream" and to follow non-existing trends, in order to be able to implement it into the work process error-free. Some of the developmental features in AI have not been fully examined or, probably, there are some completely new ones we have not witnessed yet. The fast pace by which AI enters humans' professional and personal life is providing more and more valuable data on possible weaknesses and limits of its evolution.

2. ARTIFICIAL INTELLIGENCE AND ITS APPLICATION IN LOGISTICS AND SUPPLY CHAIN

Artificial intelligence is a specific field of computer science that has targeted the development of methods that help machines perceive their environment, following an evolutionary path similar to the one of the human intelligence. Since the first introduction of the term AI in the field of software development in the 1950s, there have been many research areas of its development, but all of them have followed the goals of making AI capable of learning, planning, reasoning, and processing of different languages. In order to obtain AI's original goals, the researchers in the field during the years of its development have used many different techniques, such as mathematical optimization, statistics and artificial neural networking, in combination with certain methods from neuroscience, psychology and philosophy.

2.1. USA & North America

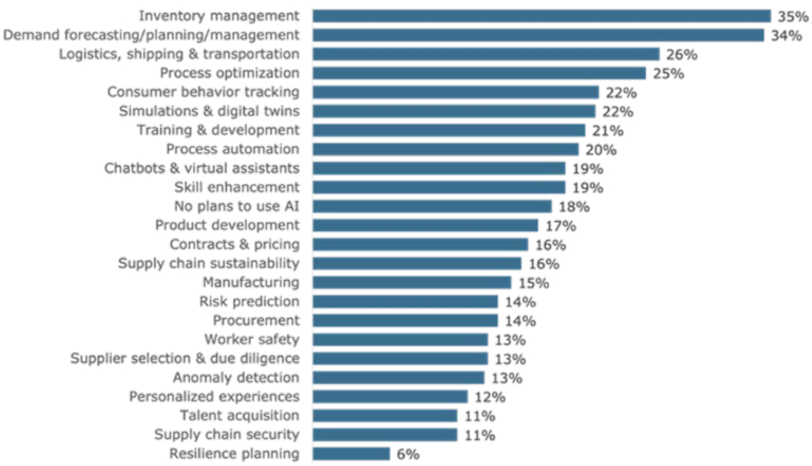
It is no surprise that, by being able to swiftly analyse multiple data sources and provide well-backed statistical data, AI has proved its value in most of logistics area such as but not limited to the inventory management processes, automated warehousing, forecasting of demand as well as possible supply disruptions. A 2024 research conducted by the MHI (Material Handling Institute) based in Pittsburgh, PA [4] shows that most of the companies that participated in the survey plan to significantly increase the adoption of the AI technology in their logistics within the next 5 years.



Graph 1 Predicted AI technology adoption, based on MHI survey, 2025

In the data it is clear that most respondents plan to invest in innovations within the next 5 years in order to keep their systems in line with modern trends. We see that artificial intelligence is one of the most targeted areas for improvement and development in logistics and supply chain and it is expected to almost triple its adoption within the next 5 years. The same research states that, following the post-COVID recovery, 55% of the respondents have the intention to increase their investment in new technologies, with 19% of them planning to invest over $10M over the next 3 years.

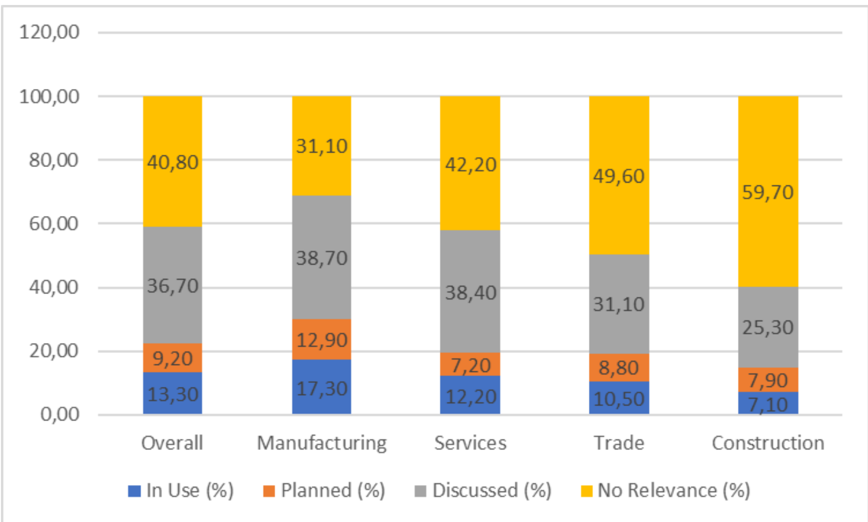
Automated supply chain solutions are the key stone to improve logistical performance of production companies and their transport solution-making partners. According to the survey, 40% of the companies that took part in the survey have already introduced (or a planning to do so) some form of automation in their supply-chain operations. In that respect, AI is clearly developing faster than the companies' ability to implement it, changing the competition factors between different companies. The potential AI has in the field of supply chain is basically limitless. In present days it is implemented into schedule optimisation, supply performance evaluation, prediction of disruptions that may need human assistance [2]. Since modern-day supply chain involves more and more different automation systems and tools, the AI in the form of agenting AI may prove to be the link between all of them. It is capable of analysing data, give options and make logical decisions based on a certain learned process but still being able to improve its own performance over time. Some applications may even go as far as the so-called drone-delivery, smart warehousing and others [3].



Graph 2. Current or predicted use of AI (Source MHI report 2025)

2.2. Europe

The situation in Europe also shows increase in the use of AI in the area. A study from the IFO Institute – Leibniz Institute for Economic Research at the University of Munich published in 2023 [6] shows that 13.3% of companies are currently using AI and 9.2% are planning to implement AI. 36.7% are discussing potential AI use cases (see graph 3). AI is most widely introduced in manufacturing, with 17,3 % of companies already using it and another almost 13% having already decided to implement it in near future.



Graph 3 Artificial Intelligence in German companies in % shares (source IFO institute, 2023)

According to a survey by Inform [7], AI demonstrates a high potential in logistics, according to German companies in the field. They consider its greatest benefit in demand forecast & sales planning (62%), followed by optimization in production lines (51%) and transport (50%). Our research clearly shows that for a period of 5 years (2019-2024) the logistic industry in Germany has transformed it opinion towards AI implementation from a visionary step to some necessary tool in order to improve production lines, deliveries, as well as customer services and chat-bot desk tools.

Nevertheless, we notice significantly lower percentage and more limited areas where AI is introduced. In Germany a trend for major companies to be more attracted to introducing AI is obvious. According to a study from "The IFO Institute" [6], approximately 33% of large companies (over 250 employees) have implemented AI, compared to just 10% of small companies. This is mostly due to the reluctance of management to introduce AI due to concerns over expertise, integration challenges, and legal uncertainties. The study emphasizes on the need of further personnel training. However, introducing of AI may be the answer to the ever-growing shortage on staff in certain areas. Asia

The situation in Asia is much the same, with AI introduced in almost every aspect of logistics, production and supply chain. It has a further significance for the area, emerging as one of the pivotal and most important areas of development for the AI due to Asia's need for advanced supply chain solutions. AI enhances significantly efficiency of production lines, addressing challenges like rising customer expectations and shortage of labour. Not only in Asia, AI is introduced rapidly in the quality monitoring [1]. In countries like Japan, where the demographic situation is a reason for a shortage of labour, AI is managing to leverage the problem. As in other parts of the world, AI is emerging as the main tool for market forecasting and planning, as well as possible supply chain disruptions.

Sustainability is another problem AI is able to address when it comes to production and supply chain lines. Sustainability has been gaining it major role for the last decade, with the introduction of various measures, designed to turn industries greener. Even with certain resistance from more conservative opinions, it is becoming more and more clear that green industry must and will become the standard rather than innovation. This transition surely comes with enhanced expenses, not only in the form of investments in new equipment but also in monitoring if processes are in line with new restrictions. [5] All analysis shows that in all parts of the world AI is introduced in this particular area because of its ability to monitor a vast amount of data. It is also introduced in risk management not only in business forecasting but also in operations.

3. MAJOR BENEFITS AND CHALLENGES REFERRING TO THE INTRODUCTION OF AI IN LOGISTICS AND SUPPLY CHAIN

Similar to all new technologies, AI comes at a price that not all companies are prepared to address. There are some significant challenges in front of operators who want to remain competitive in their performance. The modern pattern in world trade shows a significant level of uncertainty, mainly arising from political unrests, swift changes in political approach regarding world trade and the resulting inflation. All these dynamics make it harder for companies to keep up with these new trends and thus to predict an uncertain market. On the other hand, is the undoubted technical revolution AI is introducing to the world, which can only be compared to the introduction of internet some 35 years ago. Companies that want to keep their market share are aware that investment in new technologies is a must if they are to be in the future. However, the investment in new AI technologies is still too much for smaller players. New investments will have to be made and only the players who are flexible enough to make them wisely will be able to resist the new technological wave.

Another critical problem companies in logistics and supply management are predicting is the shortage of trained personnel, able to freely operate AI-based software tools. Like every other tool, AI needs to be in the hands of someone with the proper skills in order to be able to use it correctly. The technological development of AI is much faster than the ability of employers to instruct their employees how to use it in advance. They cannot rely on them having the necessary knowledge for using AI from school or other educational institution since it is only emerging and not being so wide-spread. Companies must be prepared to make significant investments in education and training for their staff.

Among the major benefits from introducing AI is the possibility to improve performance capacity for employees. All smart technologies significantly shorten the period a process is being performed and this makes it possible for one employee to perform and monitor/control a wider variety of tasks. This feature may be seen as both an opportunity and a challenge. Enhanced work productivity may prove to be of major importance in regions like Japan and EU where the population is aging and there will be a significant shortage in personnel in near future, especially in areas like supply chain/logistic processes. On the other hand, there are significant concerns that AI may even replace human workforce in near future. Even if possible, regarding low-skilled labour, the need for human personnel will never disappear, maybe because of the nature of AI itself, based on self-teaching from interaction with its environment. Thus, the need of a highly trained professional human to co-operate with AI will never disappear. Nevertheless, the wide introduction of AI in most aspects of human life will probably cause some employments to disappear or be transformed. The humanity has already seen it happen many times in the past, but there will still be areas, especially ones depending on human interaction, i.e. certain areas of customer service or education, where the application of AI will have its limits.

There is also another aspect of modern logistics and supply chain that AI can address. The sustainability in modern industry, in all its aspects, is gaining more and more importance, even with all the opposition it sometimes gets. The potential AI has to enhance productivity, to reduce waists and improve resource consumption makes implementation of various AI tools critical for enforcing the more and more strict directives regarding carbon print, renewable power sources and electricity-driven transport. Furthermore, optimizing resource consumption, the waste management and subsequent recycling contributes to diminishing the level of ecological impact a certain logistic system has and additionally improves cost efficiency of production and distribution.

Warehouse management enhancement is Another aspect which may indirectly influence the sustainability of a logistic system. More complex and strict analysis of trends in inventory dynamics contributes to more effective shipments and distribution, reducing of unnecessary shipments and on the other hand minimizing shortages. According to a report by the Sustainability Magazine [8], even with AI, as one of the most reliable tools for reaching carbon neutrality, still only 17% of worlds freight and industrial companies use it for emission reducing. The projected emission related to AI itself are projected to rise to 718 million of tones of CO_2 by 2030 due to its significant energy demand, even with the development of hardware energy efficiency. A substantial number of companies (42%) expect AI to cut emissions in short term, while more (65%) expect an impact over the next decade.

4. SWOT ANALYSIS FOR INTRODUCING AI INTO LOGISTIC SYSTEMS

Following all above data and the statistical information gathered, one can summarize the effect of introducing AI in logistic systems in the following SWOT analysis:

Table 1 SWOT analysis for introducing AI into logistic systems

Strengths	Weaknesses
- **Significantly increases productivity** and efficiency in logistics processes	- **High initial investment costs**, especially challenging for smaller companies
- **Fast data analysis** and the ability to monitor multiple processes simultaneously	- **Shortage of trained personnel** to operate and integrate AI systems
- **Reliable forecasting** of demand and supply disruptions	- **Integration challenges** and reluctance from management due to legal and expertise concerns
- **Improves warehouse management** and shipment optimization	- **AI limitations** such as potential for "hallucinations" (errors, following non-existing trends)
Opportunities	**Threats**
- **Rapid adoption and further development** of AI in logistics worldwide	- **Uncertain market conditions** due to political unrest and inflation
- **Addresses labour shortages**, especially in aging societies (e.g., Japan, EU)	- **Potential job displacement** and transformation of employment roles
- **Supports sustainability goals** (reducing waste, emissions, improving resource use)	- **Rising energy demand** and associated emissions from AI technology itself
- **Enables advanced applications** (drone delivery, smart warehousing, agenting AI)	- **Dependence on reliable human-AI collaboration**; risk if skills gap persists

Based on the a.m. analysis, one can summarize that even if there is a high level of enthusiasm of the potential benefits from introducing AI, such as improved productivity, faster data analysis, forecasting and optimized shipments, there are still some concerns regarding high cost of implementation and training of personnel. At the present moment, even if they see AI as a potential benefit for their company, most of the smaller players are reluctant to invest such a vast amount. Nevertheless, one can expect specialised AI to become more and more available with future expanding of AI technology and development.

Another aspect of introducing AI into logistic systems is it gives the opportunity to address labour shortage that is expected to appear in countries with fast declining population, i.e., Japan. However, the market volatility, following the political unrest and conflicts worldwide, combined with the ethical problem of replacing human with AI in certain processes, especially ones involving personal responsibility is making logistic companies reluctant to fully invest in large scale. Furthermore, many companies have invested significantly into developing outsourced branches. In this respect, further evaluation of AI implementation combined with outsourcing, needs thorough analysis.

Last but not the least of importance stands the environmental impact. AI has the potential to significantly reduce wastes and emissions as well as improving use of resources. Nonetheless, the impact of the high energy consumption of AI has not been evaluated fully and compared to present levels of industry impact **yet**. Since there is still not enough data (AI has been introduces only few years ago), a thorough analysis on this subject needs to be performed, based on the experience gathered.

5. CONCLUSION

The modern world is once again witnessing a major technological revolution. The potential impact of AI in life of people may be similar to the development of telegraph, of introducing the Internet or development of widely used search engines. It has the potential to revolutionize industrial world and logistics, being the frame of it, is among the first areas to experience this new impact. All the potential benefits described above can reshape significantly the way supply chain management operates. However, the voice of conservativism is strong, but not necessarily negative. It serves as a reminder that AI is a tool to be used by people and not to replace them. Furthermore, AI has limits of performance and potential to hallucinate which may even prove to be dangerous in certain matters. It cannot be used as answer to all digitalization questions logistics and supply chain management have to answer. The limits of AI's level of performance It is an important ethical issue that is yet to be addressed in its full scale. In that respect, the need for adaptation of educational systems, instructive programs and even areas of professional development will become imminent. Clearly, AI is a technology in its infancy with great potential for development. How significant its part is going be in logistic systems is yet to be discovered.

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DIGITALIZATION AND SMART PORT INNOVATIONS IN COASTAL MARINAS FOR SUSTAINABLE NAUTICAL TOURISM: A CASE STUDY OF ACI CLUB INITIATIVES

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Abstract

Digitalisation tools like Internet of Things sensors, AI analytics and cloud-based management platforms allow for real-time monitoring of safety, resources and berth occupancy in current marinas. The smart port concept involves integration of ICT infrastructures, automation of processes and data driven decision-making, and has also been extended to marinas for optimizing operations, improving eco-sustainability and enriching user experience. ACI's marina network has led Croatia's digital transformation, installing smart metering infrastructure and IoT sensors at flagship locations such as Marina Rovinj to automate energy and water management and to optimize visitor services. From its ongoing underwater robotics pilot at Marina Skradin to the upcoming implementation of smart infrastructure at Marina Rijeka, it is clear ACI has a carefully considered and complete digital provisioning plan which includes both software platforms and hardware innovations. By comparison, ACI is right in-line with advancements being made by IGY Marinas, D-Marin and MDL Marinas; all of whom use similar digital and sustainability initiatives on substantial level. Stakeholders should focus the scaling of environmental monitoring technologies across all ACI marinas and create European Union supported public-private partnerships to foster the deployment of digital infrastructure upgrades. Future research needs to assess the long-term implications of smart systems on operational performance and sustainability indicators and consider user acceptance and interoperability models for marina digital ecosystems.

Keywords: Digitalization, Smart Port Systems, Smart Marinas, Digital Sovereignty, Sustainable Nautical Tourism

1. INTRODUCTION

A strategic shift towards digitalisation is taking place in Croatia's marina industry, consistent with regional shipping developments across mainland Europe. The European Union's Blue Growth strategy – a plan for sustainable growth in the marine and maritime sectors as a whole – has identified maritime and coastal tourism as a high potential growth sector, with corresponding calls for strategic investment in nautical infrastructure including marinas [1]. These policies focus not just on competitiveness and innovation, but also on environmental sustainability. Public authorities can stimulate investments in berthing facilities and port infrastructure renovation also to decrease the carbon footprint of coastal tourism [1]. In that regard, marinas are becoming strategic centres of the blue economy with digitalization getting aligned with sustainability targets.

The idea of "smart ports" is not confined to ports, but also, marinas, with the aim of opening up nautical tourism to a technological revolution. A smart port or marina utilizes a variety of cutting-edge ICT solutions – from IoT sensors to AI-driven analytics – to improve operational efficiency, increase safety and reduce environmental impact. As Molavi et al. (2019) and other contend that in a scenario of decarbonization, ports are increasingly pressured to improve their performance in operational, energy, and environmental terms and that this has led to widespread adoption of smart technologies [2]. The smart marina has emerged from the smart port concept, targeting a set of features such as operations, energy use and the environment, but ad hoc designed to apply them to leisure ports and yacht harbors [2]. Deploying such innovations can have a substantial effect: real-time data systems may be used to improve capacity utilization and service quality, while automation results in reduced human error and resource waste [2]. In fact, company's adoption of digital technologies might lead to improved efficiency and sustainability via constant data-driven optimization [2]. But within the context of marinas being digitally interconnected, questions of digital sovereignty also emerged. Control of digital assets and data at the local level, corresponding with European values of technology autonomy, is considered as central to secure and responsible digitalisation [3]. The EU's wider digital strategy highlights the need for a transformation that preserves fundamental rights and strengthens Europe's digital sovereignty [4], a principle that is closely linked to the maritime sector as it embraces cloud platforms, smart devices and AI-based services.

The example of Croatia's marinas is of particular interest when considering these trends. Croatia is one of the Mediterranean's' most attractive nautical destinations with 78 marinas amongst its 167 nautical tourism ports along its Adriatic coast [2]. This network, which includes more than 18,000 berths, is a major component of the nation's tourism-driven blue economy. The choice to consider Croatian marinas – in particular those managed by Adriatic Croatia International (ACI) – is based on their leadership and responsiveness in implementing "smart" measures. ACI, the largest company for berth renting services in the Mediterranean, the largest chain of marinas in the Mediterranean, with 22 marinas, and the leading company of marina business in Croatia, has become a leader in digital transformation in the marina industry [2]. As an example, ACI Marina Rovinj has been changed into an integrated marina with an upgraded metering system to automatically control water and energy consumption in the port connected to the berth [5]. These enhancements illustrate the broader approach of ACI to advance digital and green business models in the context of European Union (EU's) sustainability targets [5]. The future ACI Marina Rijeka to be the most technologically advanced marina in the region is another evidence of smart and eco ports development [5]. Through an analysis of Croatian marinas, we can see how digitalization technologies – such as the online booking of berths, IoT-based monitoring, AI-based security and energy systems – are materialized and with what effects. This emphasis also provides insight into how considerations of technological sovereignty and data governance are negotiated in a tourism-driven maritime context.

In brief, Croatian marinas are at the crossroad of European policy requirements and industrial innovation, combining objectives such as technological modernization, sustainability and competitiveness in their digitalization process. This introduction has provided a strategic context for the development of 'smart port' systems in marinas, placed within the context of the EU's Blue Growth and digital agendas. The remaining part of this text examines the state of digital and smart technologies in Croatia's marina sector, with a special reference to ACI network and their impacts on on long-term resilience of nautical tourism infrastructure and business sustainability. An analysis of this kind not only provides an overview of how Croatian ports are progressing and what challenges they are faced with, but also global guidelines for the usage of ICT in the management of marinas in European environment [2]. The results are intended to inform debates about how coastal states may reconcile innovation, digital sovereignty and sustainability in the pursuit of a smart, green blue economy.

2. LITERATURE REVIEW

2.1. Smart Port and Smart Marina Concepts

The idea of the "smart port" has developed from the smart city concept, involving computerized, data-supported management of operations and the energy and environmental performance of ports [6]. There have been formalizations of models to assess the smartness of a port – the seminal work of Othman, et al. (2022), for instance, introduced a Smart Port Index with five crucial domains: the operational efficiency, environmental sustainability, energy adoption, and safety/security [7]. This underpinning theory is now being applied to marinas. The concept of the smart marina is that it is a combination of smart port and smart city in the context of nautical tourism [2]. Gallo (2023) situates smart marina development in Croatia in a systems perspective on recreational boating tourism, connecting port digitalization with smart tourism targets [8]. There is also starting to emerge an industry consensus; the International Council of Marine Industry Associations (ICOMIA) defines a "smart marina" as a facility to have completed its digital transformation journey carefully connecting physical sensors or platforms, collecting and sharing data, using analytics to manage operations and directly interacting with other community services [9]. Generally, in all such considerations, the objective is always to improve the efficiency, safety and sustainability of marinas operations [2].

2.2. Digitalization Technologies in Marinas

In the context of growing nautical tourism, marinas are encumbered by the increasing seasonality of congestion, overexploitation of resources, and environmental effects [2]. As a response, many are building intelligent tech into their operations with the aim of optimising and becoming more sustainable. To monitor and optimize the consumption of resources like water, electricity and thusly, reduce pollution, networks of sensors for Internet of Things (IoT) in combination with cloud-based platforms have become more and more frequent [2]. AI and automation increase reliability and safety of the navigation by reducing the amount of human errors in marina operation [2]. A control system of smart marina for yachts was prototyped to support safety of vessel traffic as a usage scenario [10]. Common digital tools are maritime apps where boaters can book a berth, find services and provide real-time data, as an example is the EU FAIRWAY project in the Baltic region that has developed the Smart Marina app that guides sailors and harbor information becomes available [11]. Cloud data platforms that connect the stakeholders of a marina (such as operators, boaters and service providers) are currently available, where real-time information sharing on vessel traffic, berth availability and port services can take place [12]. There is some evidence to suggest that early adopters that use digital solutions find it possible to increase process efficiency as well as to release staff time enabling more time to be spent with customers [9].

2.3. Sustainability and "Green" Smart Ports

A significant catalyst for the smart port/marina movement is its emphasis on sustainability. Smart Port initiatives have been increasingly converging with the green port concept, where they incorporate technology that mitigates pollution and wastage. For example, renewable penetration has been studied – Lamberti et al. (2015) proved the concept that moored boats could be considered as distributed energy storage/generation units in a smart port arrangement [8]. Port authorities and academicians underline environmental performance monitoring through digital means: e.g., specification of green performance indicators for ports (Bucak & Kuleyin, 2016) and sensors for air/water quality and waste in marinas (Sangprasert, 2025) [13]. Environmental sustainability is an important issue in the context of marina digitalization initiatives in the

Adriatic, and is frequently connected to eco-certification systems – e.g. Blue Flag, under which many Croatian marinas offer environmental standards [2]. Smart marinas utilize data to minimize the use of energy and water, and to waste more effectively, in the path of carbon reduction and cleaner waters [14]. For instance, the ACI marina network has implemented smart metering devices that share up-to-date information on power and water consumption per berth, for immediate leakage detection and energy saving [15]. A recent smart port review also add to the evidence that the sustainability asessment criterion is work from a first level of smart [16]. Fundamentally, technology-led efficiency goals of the smart port paradigm intertwine with the goals of sustainability development, and a further degree of synergy is sought when these issues are being rolled out in a marina setting.

2.4. Regional Developments: Croatia, Adriatic, International

Digitalization is emerging in Croatia's marinas, but it is progressing unevenly. A recent case study conducted in 78 Croatian marinas showed that the uptake of online proofing systems and digital management tools is increasing in marinas which results in better quality of services and safety [2]. However, this study also found that the state of the art in environmental monitoring and control systems is still immature, showing the delay in achieving environmentally focused digital practices [2]. Many of the most advanced marinas are owned by the Adriatic Croatia International (ACI), the biggest marina chain in the Mediterranean, which has been testing smart solutions such as automated berth traffic management and real-time resource monitoring at its flagship ports [17]. For instance, ACI's recently reconstructed Marina Rovinj is referred to as a completely digitized infrastructure with sensor-based metering and an integrated processes platform [18]. Outside of Croatia, island territories in the Mediterranean have begun capitalising on marinas as innovation testbeds, e.g. Naxos (Greece) launched an initiative to convert the island into a smart island that will have their marina retrofitted with IoT-enabled infrastructure and cloud services [12]. Similarly, a Baltic Sea EU Interreg 'Smart Marina' project up-graded 32 small-maritime systems at harbours with digital apps and green technologies (solar panels, smart waste/utilities) such that many newly up-graded ports were awarded Blue Flag eco-certifications [11, 32]. They are another example of the increasing momentum of smart marina projects throughout Europe, including in the Adriatic, where sector players are realising the advantages of digital transformation.

2.5. Identified Research Gaps and Possible Future Directions

Notwithstanding these developments, there are still impressive deficiencies on the level of practical reality and in literature. Research has also shown that more than 85% of marinas worldwide today are relatively low in digitalization and still have very little automatic function as well as data sharing [19]. Research into smart ports has generally focused on large commercial ports, while nautical tourism port has received much less attention [20] [2]. Further research should be done in the field of digital transformation of marinas, particularly in the context of the Adriatic, to identify the most effective technologies for implementation in small ports. Key questions for future research address: how environmental sensing and impact monitoring in marinas can be further developed; how to remove organisational and financial barriers for the adoption of technology; how smart systems can be interoperable across different ports and platforms. Developing customized performance indicators or maturity models for smart marinas may be a way to benchmark progress – as is currently being done for smart ports but with consideration for the smaller scale and tourism-focused functions of marinas. Finally, future studies need to consider not only technological aids but also user acceptance, staff training, regulatory support, and long-term sustainability effects. Closing such gaps will consolidate literature bases, and also support practitioners to progress the digital and intelligent port transition in the marina setting [2] [12].

3. ACI MARINA NETWORK IN CROATIAN NAUTICAL TOURISM

The backbone of Croatian nautical tourism infrastructure is the Adriatic Croatia International (ACI) marina system. Founded in the 1980s, today ACI is the largest chain of marinas in the Mediterranean, with 22 marinas (plus one anchorage) that are located from Umag in the north to Dubrovnik in the south [17]. In total, these marinas provide more than 6000 berths and accommodate close to 400,000 boaters each year [21]. As an AG company (with Croatian government as majority owner), ACI does have a prevalent role in the sector, minding over a large part of 78 registered marinas in Croatia [2]. Boaters from all around the world make the ACI their first choice due to its broad geographical setting and high levels of service and the ACI safe-harbours are a prerequisite to the development and enablement of nautical tourism to take place within Croatia [21]. These marinas are located a short distance from both historical towns and natural features and can provide sailors with the opportunity to visit a new location every day, whilst benefiting from safe moorings and consistent facilities throughout the network [21]. This unrivaled penetration and consistency once again confirms the importance that ACI has in maintaining Croatia's position as the world's leading nautical tourism destination.

3.1. Structural and Operational Characteristics of ACI Marinas

In operational aspect, ACI marinas are uniformly organized and operate on the same service principles. All marinas are administered by concession issued from local administration, and concession fee is paid by ACI for the management of the marinas [17]. Amenities: Primary services include annual, seasonal, and transient dockage, water/electricity fuel services, maintenance yard facilities, and 24/7 security. Related services (e.g. restaurants on the site, charter companies, shops) are in many cases offered by private enterprises and that enables a wide range of tourist proposal of visiting [22]. The network-wide operation, i.e ACI's headquarters in Rijeka provide uniform quality standards and pricing policies, while day-to-day management is in the hands of the local harbormasters and staff at every marina. Fast forward to 2022 and ACI employed more than 300 full-time staff throughout the marinas to maintain service quality and safety [17]. Specifically, ACI marinas operate 365 days a year in the most important charter ports for the winter boater and live-aboard, while its smaller and seasonal facilities open their doors to coincide with the warm and lucrative summer months.

In terms of human resource, as a state-owned publicly traded company (~ 79% state stake in the company), ACI has capital to frequently upgrade [17]. This model has allowed for significant modernization projects, for example the flagship of the renewal of ACI Marina Rovinj in a luxury five-anchor marina. All ACI marinas adhere to national marina categorization standards and a substantial number have been awarded with international recognitions. For instance, approximately 44% of ACI's marinas have Blue Flag eco-certification (environmental standards) and ACI Rovinj has been awarded the 5 Gold Anchors rating for quality service and facilities [15], [23]. Moreover, ACI adopted ISO certified management systems (such as ISO 9001 for quality and ISO 14001 for the environment) for the normalization of operations and to maintain ongoing adherence to safety and environmental legislations [23]. Together, these physical and operational attributes enable ACI to deliver marina services at scale and with dependability and the utmost of quality, anchoring Croatia's nautical tourism economy.

3.2. Digital Transformation Initiatives in ACI Marinas

ACI has in recent years initiated an extensive digitalisation transformation in order to bring its marinas in line with the concept of "smart marinas." This activity is in line with the general tendency in the marina business to exploit new technologies for efficient asset management and better services to customers [2], [24]. ACI's most significant achievement in this domain is 'ACI Marina Rovinj', which is widely referred to as the first fully digitalized marina in Croatia [15]. The Rovinj marina promotes advanced marina management systems, for example, intelligent traffic management of ships within the port area and an automated metering of user service connections (for the purpose of calculating the sojourn of ships and passengers in the port area, respectively) and it is a representative of smart marina concept [15]. Sensors and IoT devices watch the realtime usage of water and electricity on each berth; the data collected are communicated to a central system where staff and visitors can follow the consumption and identify that amount consumed is not normal 25. With this intelligent infrastructure, marina operators can optimize energy use (lighting, power supply) and reduce service times, as well as provide boat owners with digital tools (apps or interactive kiosks) to facilitate docking. Croatian marinas are "in the midst of a digital revolution" the study says concerning digital services such as online berth booking and e-payment which enhance convenience and safety for marina users [2]. This revolution has been led by ACI, which introduced an online centralised booking system for its marinas and a loyalty mobile app which allows ACI club members to book a slip with ease and access discounts across the network. Such innovations can diminish congestion and human mistake in berth allocation that would occur during the high season rush [2].

Apart from enhancements visible to customers, smart infrastructure networks are being rolled out by ACI in pilot projects. In 2022, ACI Marina Skradin collaborated in the EU-supported Innovacare/Innovamare pilot initiative for underwater robotics and sensor networks for marina use [26]. Underwater drones, themselves, are also hard at work: using water-quality sensors, a pilot in Skradin showed off water-quality monitors which can continuously monitor submerged structures and environmental conditions in real time [26]. Not only did this feature the latest and greatest tech to help marinas run better (like automated hull inspections or pollution detection) it also showed ACI's dedication to pushing the envelope. ACI's next project, the new ACI Marina Rijeka (Porto Baroš), is intended to be the most modern one on the Mediterranean[27]. Supported by an investment of HRK 363million, ACI Rijeka will already from the outset adopt the most up-to-date digital systems – including smart utility pedestals, parking with license plate recognition and marina management software – to establish a new landmark status for the design of the "smart port" in nautical tourism [27]. From a high-level, ACI's transformation demonstrates how a traditional Telemetry Communication Network within a marina can be transformed using smart technologies (Internet-of-Things IoT sensor information, automation, Data analytics) to improved efficiency and service. These initiatives reflect trends in marinas worldwide and confirm the perception that "smart" marinas can stimulate operational efficiency as well as improved guest satisfaction [2].

3.3. Sustainability and "Green Port" Initiatives at ACI

In parallel to digitisation, ACI has placed the focus of sustainability and environmental stewardship in their strategy, in line with the EU Green Deal and Blue Growth agendas. Marinas are inherently involved with sensitive coastal environments, so as a value proposition ACI considers environmental responsibility of the sea and coast as a central responsibility. [15]. You can see that in the various green projectsan it has going in its facilities. Foremost among other approaches are those of ACI marinas "green port" principles: environmental friendliness in marina design and operation [23]. During the reconstruction of the ACI Marina Rovinj, for example, extra attention was dedicated to eco-adapting the space: Dalmatian Mediterranean plants where planted all over the marina, whereas advanced irrigation systems were setup to preserve water [23]. Solar panels to generate electricity, solar power for hot water and energy efficient lighting are being used more widely at many of ACI's marinas. ACI Umag and some other marinas are awarded the "Green Energy" label, on account of the fact that they purchase 100% of electricity (through the national "ZelEn" program) from renewable sources to operate the facilities [23], [28]. On the company level, the ACI d.d. company has always renewed its ISO 14001 environmental management certificate, which demonstrates that the company conducted structured measures regarding the reduction of environmental impact [23]. Through these policies, ACI is one of the pioneers to make Croatian marinas green. Indeed, ACI has recently submitted an application to become a member of North Adriatic Hydrogen Valley- an EU-backed plan to develop a hydrogen fuel network - in a bid to trial hydrogen as a clean energy source at its marinas [29]. This forward thinking step could lead to emission free propulsion in port and heating company facilities with carbon neutral technologies envisioned by the European Green Deal by 2050 [23].

Sustainable operations in ACI marinas also include waste and water management. ACI marinas all have correct waste disposal (recyclables, hazardous waste, used oil, etc.) and all but one have a pump-out station for waste water, so there is no black water discharge into the sea [2]. Monthly seabed clean-up initiatives are held in both marinas, conducted by ACI employees together with local divers, to pick up garbage littering the marina bottom [30]. In addition to these annual works and ongoing water quality testing through the ACI have led to the Blue Flag now flying at the majority of ACI marinas in evidence of clean water and clean beaches [15], [23]. ACI's commitment to sustainability also reaches into community and learning; the company works with programmes such as Green Sail to educate staff and sailors in sustainable practices, and runs public awareness campaigns about marine management [23]. By funding green port-like projects ACI is responding to the aims to protect the biodiversity, reduce pollution and promote the circular economy of the European Green Deal [23]. At the same time, ACI innovations correspond to the Blue Growth strategy of the EU related to sustainable development in the blue economy, which means that growth of nautical tourism is possible while care for the state of the environment is a priority [31]. In conclusion, a combination of sustainable Infrastructure enhancement (renewables, efficient utilities), certifications and proactive conservation programmes is placing ACI amongst the leaders in sustainable marina management in the region.

Table 1 presents a comparison overview of ACI smart marina developments amongst leading international smart marina networks; indicating where ACI is positioned on the global stage in terms of digital and sustainability performance.

Table 1 Comparative summary of ACI marina smart efforts alongside leading international smart marina networks

Marina Network (Region)	Scale & Reach	Notable Smart Technologies	Sustainability Initiatives
ACI Marinas (Croatia) [21]	22 marinas, ~6,000 berths. Network spans entire Croatian coast; ~400k boaters/year.	Advanced metering & automation at flagship marinas (e.g. smart energy and water management per berth at ACI Rovinj); Online berth booking system and mobile app for customers; IoT sensors pilot (underwater robots, smart irrigation).	~50% marinas Blue Flag certified; 100% renewable electricity via ZelEn at several marinas; ISO 14001 environmental management across network; "Green port" projects (e.g. hydrogen fuel initiative, Green Sail training).
IGY Marinas (Global) [32]	23 luxury marinas across Americas & Europe (e.g. Caribb-ean, Med); caters to superyachts and international clientele.	Centralized digital platform for members; High-speed **electric vessel charging** network (fast chargers installed in IGY ports); Smart surveillance and dock management systems; Concierge apps for yacht owners.	Solar panels and 100% green electricity at key marinas (e.g. IGY Portisco); Comprehensive waste and water pollution control (oil separators, recycling); Environmental education for boaters and staff (IGY "Marina Commitment" program).
D-Marin (Mediterranean & Gulf) [33]	16 marinas in Med (Italy, Spain, Greece, Turkey) and UAE; ~14,000 berths, incl. 1,000 for super-yachts. Serves ~50,000 customers annually.	Network-wide **IoT vessel sensors** (monitoring boat battery, bilge, security) at marinas; Smart pedestals for remote metering & control of power/water; Unified mobile app for berth reservations, payments, and real-time boat monitoring.	Solar energy utilized in several marinas; Shore power and electric charging infrastructure being expanded; Certified to ISO standards (9001/14001) at multiple sites; Active participant in sustainable initiatives (e.g. exploring hydrogen fuel adoption, marina biodiversity programs).
MDL Marinas (UK) [34]	18 marinas in the UK (South Coast and inland); ~7,000 berths. Strong domestic boating base with loyalty program (Otium).	**Smart berth occupancy** system piloted (wireless sensors to detect vacant slips in real time) integrated with online booking; Custom mobile app and CRM for berth-holder reservations and rewards; Digital access control and security monitoring at marinas.	Hosts annual **Green Tech Boat Show** to promote eco-friendly marine products (industry outreach); Blue Flag awards at several marinas; On-site solar panels and recycling facilities; Pioneering green marina concepts in UK (e.g. trialing electric boat charging, incentivizing clean boating through loyalty points).

ACI Marinas has 22 marinas with approximatively 6,000 berths along the Adriatic coast of Croatia and is experimenting with advanced metering and automation in key sites (e.g., energy and water management in Rovinj), online booking and mobile apps, and Internet of Things (IoT) trials (underwater robotics, smart irrigation), while achieving approximatively 50 % certification for Blue Flag, having 100 % renewable electricity via ZelEn, ISO 14001 compliance, green port activities and hydrogen fuel trials and Green Sail training.

IGY Marinas' 23 luxury destinations across the Americas and Europe features an infrastructure of the highest of standards, including a centralized digital platform, high-speed electric vessel charging, and smart surveillance and concierge apps while being sustained by solar power installations, comprehensive waste and water contamination controls, and the IGY "Marina Commitment" environmental education program.

D-Marin's portfolio of 16 marinas in the Mediterranean and the Gulf (which offers around 14,000 berths) has introduced network-wide IoT vessel sensors for battery, bilge, and security monitoring; smart pedestals for remote metering and control; and a single mobile reservation and monitoring app and solar energy integration, increased shore power, ISO 9001/14001 certifications, and sustainability pilots in hydrogen fuel and biodiversity.

MDL Marinas' 18 UK sites (~7,000 berths) are testing wireless berth-occupancy sensors coupled to online booking, are using end-to-end managed CRM and digital access, and are progressing sustainable practice with an annual Green Tech Boat Show, Blue Flag awards, on-site solar and recycling amenities, and provision for clean boating such as electrical supply for electric vessels.

4. DISCUSSION

4.1. Synthesis of Key Insights

The results show that Croatian marinas are moving towards digitalization, where the Adriatic Croatia International (ACI) marina network is one of the organizations leading the way in the development of some "smart port" projects. ACI's flagship project, ACI Marina Rovinj, is an entirely dematerialized 5-anchor marina equipped with telemetry systems for the automatic management of energy and water resource by quay point [35]. This is a great example of Croatian marinas making use of intelligent technology to work more efficiently and increase levels of service. Innovative and cross–border cooperation such as the InnovaMare project Italy-Croatia presented an example of underwater robotic sensors employed in the ACI Marina Skradin as pilot projects that lead to the smart marina development in Croatia [26]. These initiatives are in line with worldwide developments in the marina sector, and international organizations, such as ICOMIA, emphasize that marinas all over the world should start with digitalisation to become more efficient, connected, and sustainable [36]. Croatian marinas (with ACI at the forefront), engage into a continuous, dynamic process of catching up with developed international rival marinas through the application of smart-port concepts and technologies. The level of digital penetration across all marinas, though, is patchy, and upon a close examination there are both strengths and weaknesses.

4.2. Strengths and Current Achievements

The digital solutions to date have delivered visible operational and service benefits. Today, in many Croatian marinas, e-booking, e-payment, berth, reservation, and security via video control, are available [2]. Implementing such solutions makes management easier and takes workload off employees, ultimately benefiting the customer. In fact, Croatian marinas are in the midst of a revolution when it comes to making a berth and improving safety and service quality. Preemptive maintenance and security at docks is also bolstered by the use of smart sensors (battery status, bilge water, smoke and fire detection, etc.) from an early stage [2]. Together these technologies help marinas be more efficient – by eliminating human error and congestion through automation and streamlining of the required tasks – saving time and money improving profitability. In addition, some marinas are using digitalization to contribute towards a more sustainable future. Tehnomont Marina Veruda, for instance, installed electric vehicle charging and employs e-bikes/scooters for staff transport, thus reducing fuel consumption and emissions. At the same time the world's leading ports and marinas are also implementing such similar green initiatives (motion-sensor smart lighting that consume far less electricity for example…), so it's clear that Croatia's developments are still keeping step with the rest of the world's best practice as well. Fortunately, the better services from digitalisation are already being transferred to higher customer satisfaction and competitive development. Smart systems increase the quality of service; the latter translates into attracting of a new type of customers and the opening of new markets in nautical tourism [2]. This positive-sum relationship – improved services yield greater demand, which drives further improvement in services – indicates that digitalization can lead to sustainable growth within Croatia's marina industry.

4.3. Limitations and Challenges

Nevertheless, smart port state of the art systems in Croatian marinas have also important shortcomings. The integration of all-encompassing "smart marina" technologies is still in its infancy and fragmented [2]. Most digital solutions offer operational convenience (booking, payments, surveillance) and to some extent, energy management, whereas only few marinas have adopted advanced applications such as real-time weather and sea condition sensors, smart access cards or automatic vessel tracking (DockWalk systems) [2]. Of particular note is the above-mentioned stretch regarding environmental monitoring and sustainability indicators. Sensors, for example – particularly those that are IoT activated and used to monitor water quality, pollution levels or waste – have actually been somewhat overlooked, and which form key aspects of eco-friendly marina operations. That is to say operation KPIs currently rule digital systems, while environmental aspects emerged as the underdeveloped ones in Croatian smart marina. This gap is the central drawback of the status quo – an inability to monitor and control pollution factors: the emissions of waste, noise, and use of material in real-time [2] [23]. Resolution of this deficiency is vital for the marina industry to meet progressively strict environmental standards. In addition to the environmental differences, there are general barriers to digitalisation that stakeholders encounter. The cost of smart infrastructure can also be expensive to install and maintain and can spread a burden on marina budgets while new systems can be complex to use and maintain and requires staff training. Furthermore, the overreliance on data and interconnection brings data security and privacy concerns, as security lag is a point of weakness that must be accurately addressed in the smart technology operation [2]. Lastly, there is the human dimension where automation of tasks (from booking to handling a vessel) may reduce the requirement for some manual job positions thus bringing about the need for reskilling the workforce and careful change management [2], [23]. These constraints highlight that despite progress, a comprehensive smart port environment in Croatian marinas is still evolving and needs further development.

4.4. Strategic Recommendations for Stakeholders

Based on the previous analysis, the following strategic initiatives can be suggested for the Croatian nautical ports in order to develop the digitalization and obtain its benefits:

1. For ACI and Marina Operators: Scale up and integrate successful innovations [26]**.** Expanding on pilots such as that of ACI Rovinj, advanced metering and sensor systems should be introduced throughout the entire marina network. Environmental sensors (water quality measuring devices, smart garbage management, air/noise pollution detection) should have priority to fill the current sustainability gap. Investment in integrated digital platforms which connect berth management, customer services and environmental data, will drive an effective data-driven marina ecosystem. Best practices should also be leveraged internally, and training offered so staff can leverage new smart systems.

2. For Croatian Policymakers and Regulators: Provide supportive policy frameworks and funding [37]**.** Decisions-makers need to perceive marinas as a fundamental asset to the success of smart tourism and smart cities. This might involve the co-funding of digital infrastructure investment (which could be financed by EU blue growth and green transition funds) and the establishment of industry standards for smart marinas. Regulations can drive sustainability – by, for example, requiring large marinas to measure water pollution or giving tax benefits to green technologies. Developing instruments to allow for public-private collaboration (like the Interreg projects) will also facilitate that marinas will be more capable to test new technologies with low risks.

3. For Technology Providers and Innovators: Tailor solutions to marina needs [36]**.** Tech companies and startups that focus on IoT technology and software could collaborate with Croatian marinas to be able to offer easy-to-use and cost-effective solutions that are made for, not just adapted for, the operations of a leisure port. There are opportunities for the use of AI for predictive maintenance, digital twin models for marina assets and mobile apps, which are easy to use for visiting boaters. Local innovators can observe the state of the world maritime industry – such as the ICOMIA Smart Marinas Initiative – to make sure that Croatian marinas take up global standards, and solutions that enhance interconnectivity, data analytics, and sustainability.

4.5. Future Outlook and Research Directions

Further digitalization of Croatian marinas will bring greater efficiency and sustainability, as new opportunities are opening up, provided we have continuous innovation and favorable regulatory framework. Looking ahead marinas will indeed transition to smart nautical ports that integrate berthing and services in an efficient manner and will partly also take the role of an active actor in coastal environmental management (e.g. water pollution detection or nautical activities carbon footprints analysis). To facilitate the achievement of this, emerging research should aim to understand the long-term impacts of current smart solutions in marinas – for instance, economic benefits of digitalization (i.e. higher energy efficiency, cost reduction and improved customer satisfaction). Additionally, it would be useful to examine user acceptance and stakeholder adoption of such systems to ensure that technological features meet both the boaters' and marina management needs. On the innovation side, pilot projects using new technologies (e.g. AI based navigation system, blockchain payment and identification or security drones) can contribute to positioning Croatia as a front-runner in smart marina development. Finally, strong policy support and international cooperation will continue to be critical. EU initiatives and international best practices can help Croatia to foster an environment for smart ports: a platform that allows experimentation, knowledge-sharing and replication of best practices in all its marinas. Overcoming the deficiencies and disengagement with the development of a smart port, the Croatian marinas would be able to maximally use this smart port vision for strengthening their competitiveness in market of nautical tourism, and enhance their influence over the blue growth sustainability [2].

5. CONCLUSION

The Croatian marinas, managed by ACI, demonstrate how a national operator has the capability to lead the change towards smart and sustainable nautical tourism. Embracing the smart port concept and based on IoT sensors, AI analytics and digital platforms, ACI is able to switch a facility like Marina Rovinj to a digitalized, energy managed hub with increased operational efficiency and guest satisfaction. The strategic position of the ACI network and its standardised service procedures contribute to Croatia's efforts to sustain and foster the blue economy concept; accommodating nearly 400,000 nautical tourists annually, and setting the standards in marina management, for Croatia, as a maritime nation.

Comparison to other nautical port operators shows that ACI's smart initiatives (i.e., advanced metering, E-booking platforms and green port projects) resemble those of global nautical port operators are D-Marin's IoT vessel monitoring and MDL's smart berth occupancy systems. Findings from the literature indicate indicate that even though digitalization has significantly increased efficiency and safety, it has also left weaknesses in environmental monitoring and cyber security. Narrowing these gaps will take coordinated data strategies and targeted investments in infrastructure

Strategic recommendations are to adopt system-wide deployment of environmental sensors to achieve real-time pollution control and resource use optimisation, and develop European Union-supported public-private partnerships to finance the necessary digital infrastructure upgrading. Suggested potential future research directions are that marinas should combine digital twins with human intervention for predictive management and should encourage cross-border R&D connections, which may accelerate advanced smart marina innovations.

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ADVANCED MANUFACTURING METHODS IN THE SHIPBUILDING INDUSTRY

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Abstract

Modern technologies, such as 3D printing, have become widely available and relatively inexpensive, enabling their use not only in large enterprises but also by private users. Thanks to their easy availability and intuitive operation, people can use these devices without specialist training. As a result, this technology is gaining importance in all industries as they dynamically develop their production processes. However, despite a wide range of applications in various industries, the shipbuilding industry still uses it to a limited extent. This paper explores the potential of advanced manufacturing methods, including 3D printing and other innovative technologies. It indicates possible directions of their application in the shipbuilding industry, both in the context of shipbuilding and operation and maintenance.

Keywords: 3d printing, advanced manufacturing, spare parts, repairs

1. INTRODUCTION

The modern shipbuilding industry is facing growing technological, environmental and economic challenges. Global pressure to reduce the weight of vessels, shorten production times, and increase material efficiency makes traditional manufacturing methods, such as machining, welding, and casting, less and less competitive.

The answer to these needs is advanced manufacturing technologies (AMs), revolutionising how ship components are designed and manufactured. Currently, many technologies on the market allow printing from many materials [1]. The development of additive manufacturing (AM) technology has led to various processes that differ in their mechanisms of action, types of input materials, energy sources, and ranges of applications. To organise the nomenclature and enable comparability of research results, the International Organisation for Standardisation (ISO), in cooperation with ASTM International, developed the ISO/ASTM 52900 document, which defines basic concepts and classifies AM technologies independently of the material or industry of application [2], [3], [4].

1.1. Additive Manufacturing by technology

The ISO/ASTM 52900 standard distinguishes seven main categories of additive technologies, which include methods using metal powders and polymers, as well as materials in the form of wire, liquid resins or sheets. Each category is described in a material-neutral manner, allowing it to be applied across various contexts, including metals, plastics, ceramics, and composite materials. The classification of AM technologies is presented in Table 1.

Table 1 AM classification summary according to ISO/ASTM 52900

Process Category	Example of use	Work principle
Material extrusion	FDM, FFF	Extruding material through a heated nozzle
Vat photopolymerisation	SLA, DLP	Curing liquid resin with UV light
Material jetting	PolyJet, MultiJet	Spraying and curing a drop of resin or wax
Binder jetting	ExOne, Voxeljet	Bonding layers of powder with a binder (e.g. sand, metal)
Powder bed fusion	SLM, EBM, DMLS	Sintering or melting powder with laser or electron beam energy
Sheet lamination	LOM, UAM	Cutting and joining layers of paper, metal or plastic sheets
Directed energy deposition (DED)	WAAM, LMD, EBF	Deposition and melting of material (wire or powder) in real time

The shipbuilding industry seems to be interested in the technologies mentioned above. Still, experience shows that obtaining metal parts and small plastic parts is most difficult, especially on board a ship. Thanks to the ability to create elements with complex geometry without the need for moulds, matrices or cutting tools, 3D printing is becoming a real alternative or complement to traditional methods of building vessels. 3D printing from plastics such as ABS, ASA, or PETG is used in the production of ship interiors, electronics housings, and components with complex geometries. FDM and resin printing technologies are used to create yacht equipment elements, such as dashboards or rudders, which allow for high personalisation and weight reduction [5].

In shipbuilding, special attention is paid to metal additive manufacturing technologies. According to the ASTM F2792 standard, metal additive manufacturing technologies are divided into powder bead fusion, directed energy deposition, binder jetting and sheet lamination. Powdered metal printing is an expensive and inefficient technology. It involves a complex, physical, and chemical metallurgical process that exhibits various types of heat and mass exchange, as well as, in some cases, additional chemical reactions [6].

In connection with the above, an interesting direction of production is the use of welding wire. This approach allows for reducing printing costs and significantly increasing design possibilities. Depending on the type of energy used, such printing can be divided into three groups [7]: laser-based (WLAM), arc welding-based (WAAM) and electron beam-based (EBF). WAAM uses an electric arc as a heat source to melt the wire and form subsequent layers. The highest material deposition efficiency among wire methods characterises this technology. The process efficiency of up to 10 kg/h makes it cost-effective for significant components. However, due to the low control over the arc, the influence of the deposition sequence and interlayer cooling, it is characterised by worse geometry reproduction and part strength. Despite its imperfections, this technology has already been used to build a bridge in Amsterdam [7], demonstrating its potential (Fig. 1).

Figure 1 MX3D printed bridge in Amsterdam

Source: https://parametric-architecture.com/mx3d-steel-bridge-in-amsterdam/; https://strangesounds.org/2021/07/world-first-3d-printed-steel-bridge-amsterdam-video-photo.html

The second of the mentioned technologies is EBF. It is a NASA-patented method that utilises an electron beam in a vacuum environment to melt wires and produce metal components. It is mainly used in the aviation industry. EBF is characterised by the highest printing precision among wire methods, while maintaining a high deposition speed. Moreover, research [7] shows that the prints are characterised by excellent mechanical properties, regardless of the process parameters. This method requires the process to be carried out in a vacuum chamber, significantly increasing infrastructure costs. However, it is promising in the context of the space industry.

Wire and Laser Additive Manufacturing (WLAM), utilising the wire laser deposition method (WLDM) technology, is a technology for additive metal production, where the energy source is a laser beam. A typical WLAM system consists of a laser, an automatic wire feeder, a numerically controlled worktable (CNC) or a robot arm, and auxiliary systems, such as a gas shield, a heating or cooling system. During the process, the laser generates a pool of liquid metal on the surface of the substrate, to which the wire is fed. The wire melts in the pool, creating a metallurgical connection with the substrate. The relative movement of the laser head and the wire feeder, in relation to the base material (or vice versa), results in the formation of successive paths and layers of material. This movement can be done using an industrial robot or a CNC table [8]. WLAM is characterised by great flexibility in the selection of materials – alloys based on iron, titanium and aluminium were tested. The Ti-6Al-4V alloy is of particular importance in this technology, as its mechanical properties and corrosion resistance have enabled it to find wide application in the aviation industry. The diameter of the wire used is usually in the range of 0.2 to 1.2 mm. Key aspects influencing the quality of the process include geometric accuracy, surface condition and mechanical properties of the deposited material (such as strength, hardness or residual stress level). These parameters are strongly dependent on the wire's properties (e.g., chemical composition, diameter) and the process conditions, such as the direction and angle of wire feeding, its speed, laser power and welding speed.

Current wire-based additive manufacturing systems utilise both infrared (IR) and blue lasers, with each exhibiting distinct interaction mechanisms depending on the material's optical properties. The laser wavelength directly affects energy absorption, process efficiency, and melt pool stability, particularly in the case of highly reflective metals.

Fibre lasers in the IR range (~1064 nm) are widely used due to their effective absorption in titanium, nickel alloys, and steel. However, their absorption efficiency drops below 10% for copper and aluminium, necessitating higher power input and increasing thermal losses and process instability [9].

Blue lasers (450–488 nm), by contrast, provide greater than 60% absorption in copper, resulting in significantly improved energy coupling, reduced reflection, and enhanced process control [8]. Their shorter wavelength also enables a tighter beam focus, allowing for the precise melting of thin wire feedstock and higher resolution of printed features.

Example implementations demonstrate that utilising WAAM or WLDM in the production of ship propellers enables a significant reduction in production time, material waste, and geometry optimisation in terms of strength and weight [10]. Moreover, internal voids (Fig. 2) can be filled with materials such as polyurethane foam, which, in the case of warships, can significantly reduce the acoustic signature.

Figure 2 Example of making a ship propeller by a robot equipped with the Meltio Multi-laser IR Deposition Head

Source: Author

In the context of the maritime industry, additive manufacturing technologies from materials such as concrete [11] and technical ceramics are also worth mentioning. 3D printing from concrete, carried out directly from a cement mixture, enables the production of port and shipyard infrastructure elements, including quays, breakwaters, navigation pylons and dock elements. Eliminating the need for traditional formwork and the freedom of geometry modelling translate into significant material savings and simplification of design processes, especially in coastal and hydrotechnical applications.

In turn, 3D printing from technical ceramics, including polymer-derived ceramics (PDC) [11], enables the production of components with high temperature and chemical resistance. In the marine environment, potential applications include thermal insulation, exhaust system components, sensor covers, and components of cooling and filtration systems designed to operate under aggressive environmental conditions.

It should be emphasised, however, that the applications listed – although important – can be successfully implemented in land conditions or by specialised subcontractors. Therefore, this article focuses on the possibilities of implementing additive manufacturing technologies using metals and polymers directly on board vessels, emphasising the shortening of supply chains, improvement of operational flexibility, and enabling local production and repair of components in offshore conditions.

2. CASE STUDIES FROM LITERATURE

The application of 3D printing technologies in the maritime environment is increasingly well-documented, both in scientific literature and industrial practice. The following case studies illustrate the tangible benefits of implementing additive manufacturing (AM) in the shipbuilding sector, particularly for emergency repairs, production of critical components, and support for military operations.

Article [3] presents numerous examples of additive manufacturing use in both commercial and naval shipping. One such case involved the production of a pump impeller made from polyamide (PA12), completed in just 18 hours, with total manufacturing costs over 70% lower than those of conventional procurement. In another instance, the repair of a damaged diesel engine component using metal 3D printing reduced the price from USD 31,000 to USD 4,000.

The author emphasises the need to develop mobile, container-based AM laboratories, particularly for deployment in military operations and humanitarian missions. According to the analysis, by 2028, up to 30% of key components in the maritime industry could be produced using additive technologies. The elements most suited to additive manufacturing include valves, fittings, knobs, and spacer bushings, whose availability in operational conditions is often limited.

In June 2023, the USS Bataan (LHD-5), an amphibious assault ship, was equipped with the Phillips Additive Hybrid manufacturing system, which integrates a Meltio3D wire laser deposition head (DED) with a Haas TM-1 CNC milling machine. This hybrid setup enables the combined use of additive and subtractive techniques, allowing components to be fabricated directly onboard. 316L stainless steel, a material widely used in US Navy systems, is employed as the feedstock.

The first documented application involved the production of a sprayer plate for an air compressor in the de-ballasting system. The entire process – from need identification to part installation – was completed in less than 18 hours, avoiding an estimated USD 400,000 in costs and a potential one-year delay resulting from a conventional replacement procedure.

Additionally, the vessel is equipped with a polymer 3D printer used to manufacture parts compliant with over 300 Technical Data Packages (TDPs) developed by NAVSEA. This system ensures that the printed parts meet both geometric and functional design requirements. For example, the crew produced a small connector for the aircraft launch and recovery system, which, being below the lowest replaceable unit (LRU), was unavailable as a standalone spare part [12], [13], [14].

In 2017, at the Port of Rotterdam, RAMLAB, in collaboration with Damen Shipyards Group, Autodesk, and Bureau Veritas, produced the world's first class-approved ship propeller using WAAM technology. The propeller, measuring 1300 mm in diameter and weighing 180 kg, was made of bronze and installed on the Damen Stan Tug 1606. This project demonstrated that WAAM technology is capable of producing significant, critical components with complex geometries, opening new opportunities in the maritime sector [15].

The Dutch company CEAD is developing 3D-printed boats made from high-density polyethylene (HDPE). At its Maritime Application Centre, a 12-meter robotic printer is used to manufacture vessels up to 12 × 4 × 2 meters in size in under 50 hours, with minimal labour involvement and correspondingly low production costs [16].

Royal3D introduced the ShearWater water drone, designed for maintenance and surveillance in harsh maritime environments. The drone is made from thermoplastic polymers and PETG-reinforced materials, offering high strength, rigidity, and impact resistance while remaining lightweight and waterproof [16].

In 2023, Al Seer Marine, in cooperation with Abu Dhabi Maritime, built the largest 3D-printed vessel in the world – an 11.98-meter-long water taxi. The boat was entered into the Guinness World Records, surpassing the previous record held by the 3Dirigo boat from the University of Maine [17].

2. THE CONTAINER-BASED REPAIR CENTRES CONCEPT

In light of these arguments, using existing ship workshops or building container repair centres seems the most reasonable approach. Both the Navy and industry are working on this subject [18]. An example of advanced activity in this area is the ErectorCraft company, which launched the production of hulls using the 3D printing method from HDPE plastics in the United States. The company offers large-format ErectorBot LFAM (Large-Format Additive Manufacturing) systems and also develops concrete printing technologies for infrastructure applications in the marine environment. In turn, in cooperation with the American Bureau of Shipping (ABS), the HD Hyundai concern is conducting tests of printing metal components directly on ships. The tests focus, among others, on producing watertight doors and steel fittings, shortening the spare parts supply chain, and increasing the operational independence of units. The United States Navy (U.S. Navy) has implemented polymer 3D printers on board selected ships. The use of printed valve manifolds in underwater and surface systems has already been approved, which sets a significant precedent for AM integration in an environment with high safety and reliability requirements. The European company CEAD Group is developing hybrid ship structures combining thermoplastics and carbon fibres. As part of a dedicated Maritime Application Centre, it researches and produces components for hulls and internal structures with increased strength and lower weight. The Royal Navy is conducting field tests of mobile 3D printing units designed to rapidly produce spare parts directly on board frigates and destroyers. The project aims to increase the operational independence of the fleet during long-duration missions and reduce dependence on logistics chains..

Classification societies are also actively supporting the development of AM. DNV has launched a fast-track certification program for additively manufactured marine components covering plastics and metals. Their technical guidance, DNV-ST-B203 Additive manufacturing of metallic parts [19], aims to speed up the process of approving new parts for use in marine environments. Lloyd's Register has published guidelines for approving additively manufactured parts, with a focus on durability tests and resistance to environmental factors. The document LR-GN-046, Guidance Notes for the Manufacture, Testing, and Certification of Additive Manufactured Metallic Parts [20], provides a basis for verifying the safety of printed parts that may be used on board vessels.

This article presents the concept of a containerised repair centre, with the possibility of adaptation on board ships. Similar commercial solutions already exist, but no integrated system has been found that constitutes a single whole. For example, Snowbird Technologies presented the SAMM Tech product [20]. It is a containerised 3D printing and CNC machining system, capable of producing large parts from metal, plastic and composites. This system is designed for use in challenging environments, such as military operations or remote industrial settings. Re: 3D developed the Gigalab system, a mobile 3D printing laboratory located in a container, that processes plastic waste into new products (Fig. 3) [21].

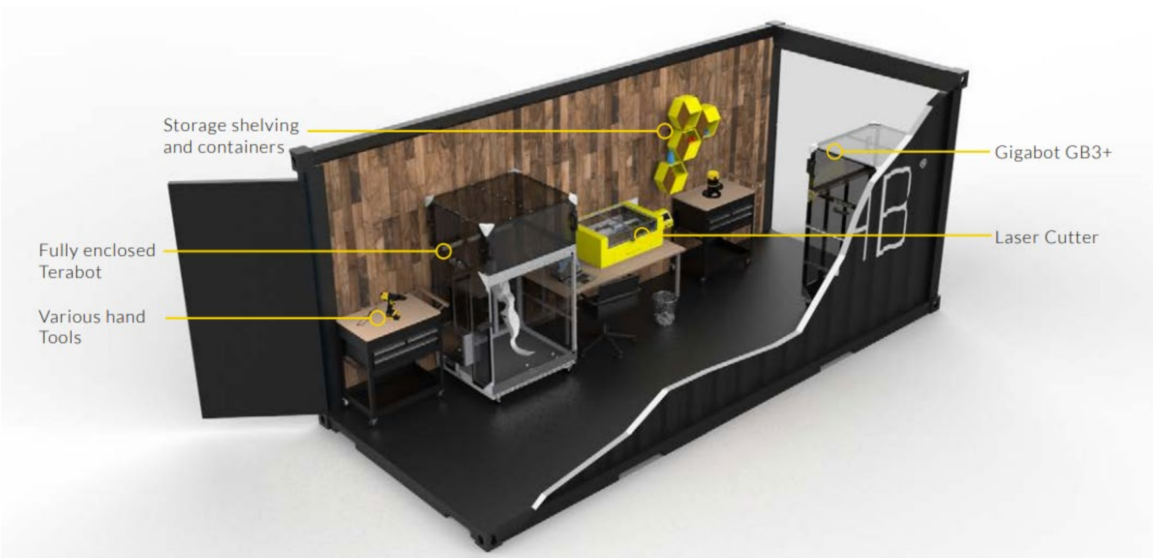

Figure 3 Gigalab container

Source: https://re3d.org/wp-content/uploads/2022/02/Gigalab-brochure.pdf

Despite their innovative character, existing solutions do not offer a comprehensive approach to maritime applications. In response to these limitations, a concept has been developed for an integrated production system that includes 3D scanning of components, processing of the obtained models, and their preparation for additive manufacturing.

For polymer elements, minimal post-processing is usually sufficient. Greater challenges arise when printing metal components. While powder-based metal sintering technologies offer high quality, they are expensive and require strict material storage conditions, which are difficult to maintain in marine environments.

An alternative is offered by WAAM and WLDM technologies, which rely on wire-based deposition. These methods typically require printing with added material allowance, enabling subsequent machining to achieve the desired geometry (see Fig. 4). Despite this drawback, these technologies offer significantly lower costs, higher efficiency, and a broader range of compatible materials, which is particularly advantageous for shipbuilding and offshore use.

a)
b)
c)

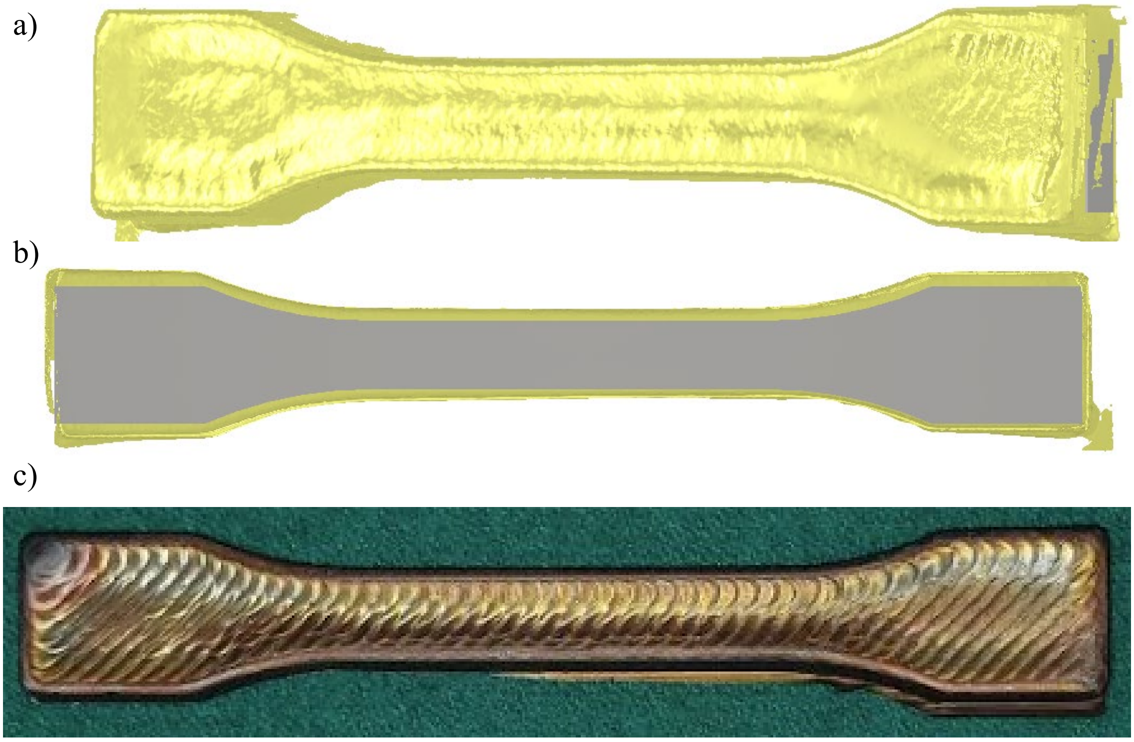

Figure 4 Imaging of the material allowance based on strength test samples, a) 3D scan of the printed sample, b) comparison of the scan and the design, c) printed sample

Source: Author

The proposed solution involves the development of a mobile, autonomous production unit housed in a standard ISO shipping container. The system enables the execution of a whole engineering workflow – from digitising damaged components, through additive manufacturing, to final machining. Its mobility and compact design allow for deployment in remote or time-critical environments, such as ships, shipyards, military bases, or offshore platforms.

The production process begins with 3D scanning, enabling the rapid and accurate capture of the geometry of worn or damaged parts. The data is then processed locally on a workstation equipped with CAD/CAM software, where toolpaths (G-code) are generated for either the FDM printer or the metal printer, depending on the component. The FDM printer is used for rapid prototyping of plastic elements, such as handles, housings, or covers, and can also print flexible parts made from rubber-like materials. The metal printer, using a wire-fed process, produces mechanically robust components from materials including stainless steel, titanium, Inconel, or aluminium. Once printed, the metal part is mechanically removed from the build plate using a band saw. The final stage is finishing machining, typically performed on a 3-axis milling machine or lathe, depending on the component's shape and function. This ensures dimensional precision, surface quality, and functional performance.

It is essential to note that the system does not include an independent power source and is therefore intended primarily for deployment in shipboard or shipyard environments, where a stable power supply is readily available.

Unlike currently available solutions – such as SAMM Tech, Gigalab, or CEAD platforms – the proposed system offers complete integration of all production stages, combining both FDM and WAAM/WLDM technologies in a single unit, with a 3D scanner as a built-in module. The production workflow is designed as a closed-loop process, enabling self-contained engineering tasks that do not rely on external design or manufacturing support. The system has been optimised for maritime conditions, accounting for space limitations, humidity, vibration, and the need for autonomous operation without land-based infrastructure.

An additional advantage is the inclusion of CNC machining, which enables the production of functional components with final tolerances and surface finishes, thereby eliminating the need for separate post-processing systems. The entire process can be handled by a trained onboard team, increasing the vessel's operational independence.

The proposed concept distinguishes itself through its comprehensiveness, integration of multiple production technologies, incorporation of 3D scanning, and complete adaptation to maritime environments. Its implementation may significantly enhance fleet flexibility, shorten supply chains, and enable local manufacturing of spare parts in emergencies.

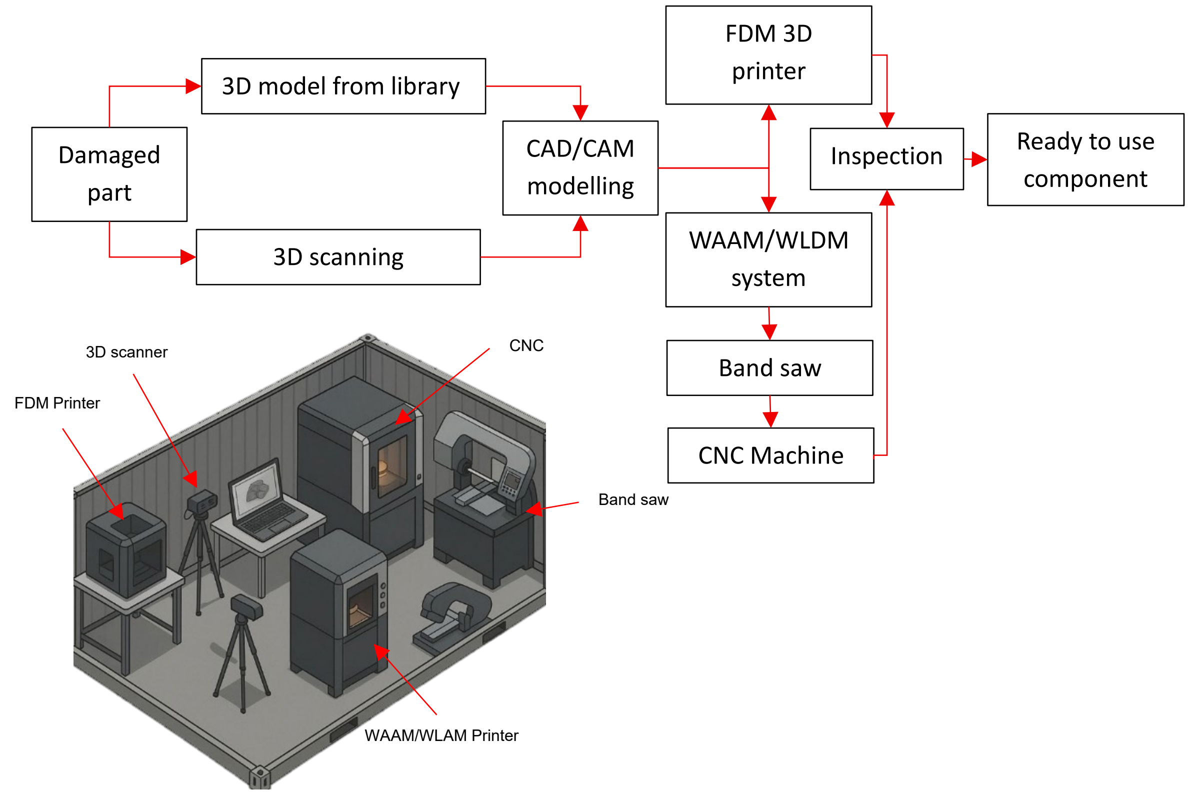

Figure 5 Schematic representation of the production process and visualisation of the layout of the proposed container-based system.

Source: Image generated by AI

3. CONCLUSION

This article presents an in-depth analysis of the potential applications of advanced manufacturing methods, particularly additive technologies, in the shipbuilding and maritime support sectors. Special attention has been given to the role of 3D printing with polymers and metals, especially the WAAM (Wire Arc Additive Manufacturing) and WLAM (Wire Laser Additive Manufacturing) processes. These technologies, owing to their material efficiency, lower operating costs, and compatibility with marine-grade metals, are increasingly viewed as a viable alternative to conventional manufacturing methods for spare parts, structural components, and shipboard equipment.

Although the technologies employed are not novel in themselves, the distinguishing feature of the proposed solution lies in their comprehensive integration within a single, mobile, and autonomous unit. By consolidating the entire engineering workflow – from 3D scanning and digital modelling to additive manufacturing and final machining – into a standardised containerised system, the concept offers a fundamentally new approach to onboard and remote technical support.

The proposed mobile production unit, equipped with a 3D scanner, FDM printer, WAAM/WLAM metal printer, band saw, and CNC machine, is particularly suited to maritime conditions, where access to onshore workshop facilities is limited and rapid response to technical failures is critical. Such a system can drastically reduce logistical dependencies, enable local manufacturing of unavailable or customised parts, and significantly increase the operational autonomy of naval and commercial vessels. This is especially valuable during extended military deployments, offshore operations, or polar and expeditionary missions, where long supply chains and downtime are unacceptable.

Moreover, the concept supports sustainable and on-demand manufacturing, minimising the need to carry extensive inventories of spares and allowing production to be tailored precisely to current operational needs. In the longer term, it may also contribute to reducing lifecycle costs and enhancing the resilience of naval support systems.

Effective operation of a container-based production unit requires access to personnel with a high level of technical expertise, including skills in CAD/CAM modelling, additive manufacturing process control, CNC programming, and quality assurance. The success of the system hinges not only on the hardware configuration but equally on the competence of its operators. Inadequate training or lack of interdisciplinary knowledge may result in low production efficiency, compromised part quality, or even equipment damage.

Another significant limitation is the lack of formal certification for components produced at sea. Without complete documentation of materials, processes, and traceability, parts made on demand cannot be used for permanent installations in classed vessels or critical systems. As such, they should be considered interim or emergency solutions, intended for restoring operational capability until a certified replacement can be installed. To ensure safe use, each component should undergo a documented risk assessment and, whenever possible, be subjected to dimensional inspection and mechanical testing.

In conclusion, the concept of a mobile, containerised additive manufacturing system holds great promise for transforming maintenance, repair, and support operations in the maritime sector. Its adoption could significantly enhance the self-sufficiency, responsiveness, and flexibility of fleets operating in remote or resource-constrained environments. Nevertheless, its implementation should be approached with due consideration of operational constraints, technical staffing requirements, and regulatory limitations.

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METHANOL AND AMMONIA AS ALTERNATIVE FUELS FOR ICEBREAKING OPERATIONS IN THE NORTHERN BALTIC SEA

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Abstract

The Arctic and sub-Arctic regions are vital for trade and energy but present environmental and operational challenges. Icebreaking fleets are heavily reliant on fossil fuels and solutions are required to meet EU and IMO climate goals. This study evaluates methanol and ammonia as alternative fuels using the Estonian Winter Navigation System simulation model. Methanol offers near term viability due to engine compatibility, but with higher costs and lower energy density. Ammonia presents a long term option but faces technical and safety barriers. Results highlight the need for technological advances and regulatory support to enable sustainable icebreaking operations under evolving climate and policy conditions.

Keywords: winter navigation, system level simulation, icebreaker fuel consumption, alternative fuel, ammonia, methanol

1. INTRODUCTION

The presence of sea ice significantly complicates shipping in the Northern part of the Baltic Sea. Moreover the temporal and spatial variation of ice parameters makes it less predictable hindering transportation, operational reliability, and long term sustainability. Several countries in the region have established centralized systems providing icebreaking assistance through coordinated frameworks known as Winter Navigation System (WNS). A typical WNS consists of ship traffic, icebreakers, and a regulatory organizational framework setting up the principles of their operation. The required icebreaking assistance (number, location of icebreakers and their characteristics) in specific ice conditions depends on the icebreaking capabilities of the ship traffic: the less ice-strengthened the ships, the more icebreaker resource is needed. The WNS is designed to ensure safe, reliable, and uninterrupted shipping throughout the winter. It also imposes some minimum size and ice class requirements on the ships to ensure safe and efficient operations. Moreover ships must be built and operated following the corresponding ice-class rules applied in the region.

Climate change will affect future ice conditions, so the maximum ice extent and average ice thickness might decrease [10]. At the same time climate change is also projected to bring stronger winds and rougher sea conditions, intensifying ice dynamics. This makes the ice more dynamic, results in a higher possibility of forming ridged ice, and makes the ice conditions more spatially variable, fragmented and less predictable [5].

The size of a typical ship seems to grow in the future [1], while increasingly stringent environmental regulations will lead to a reduction in installed engine power. Regulatory frameworks by the International Maritime Organization (IMO) [7,8,9] and the European Union (EU) [2], aim to reduce greenhouse gas (GHG) emissions from shipping by promoting energy efficiency and alternative fuels. These regulations influence ship design by limiting propulsion power and encouraging optimized hull forms which and may significantly impact the ice-going capabilities of vessels. This could increase the demand for icebreaker assistance making it essential to develop and apply system-level simulation tools that can evaluate long term impacts of regulatory measures on icebreaking demands and energy use.

Considering the importance of supporting the interannual maritime transportation of goods and passengers this paper is based on the WNS of Estonia. The comprehensive report done by a large consortium (Tapaninen et al., 2023 [5]) is our starting point. Based on these results authors focus on quantifying the fuel consumption of icebreakers under varying winter scenarios. Icebreaking services play a pivotal role in ensuring the accessibility of ports and maritime routes during winter months, but they also contribute significantly to carbon emissions due to their reliance on conventional fossil fuels. This study analyses the fuel consumption of icebreaking vessels using methanol and ammonia to enhance the sustainability of icebreaking operations. The objective of this paper is to evaluate the feasibility and implications of methanol and ammonia as alternative fuels for icebreakers in Estonia. The remainder of this paper is structured as follows. We first present the cargo flows and shipping statistics to/from the Estonian harbours. Thereafter the WNS is introduced and the tool is used to determine the amount of fuel used on the icebreakers on a mild, normal, and severe winter. Finally the cost of replacing conventional diesel oil with methanol and ammonia and assessing the associated economic and environmental trade-offs is presented.

2. ESTONIAN WINTER NAVIGATION SYSTEM

2.1. Ports in Estonia

Estonia's main trading partners are its neighbours. In 2023 [15] export volumes reached 18.2 billion Euros, with main export partners Finland 16.9%, Latvia 11.9%, Sweden 9.4%, Lithuania 8.2 %, Germany 6.6%, USA 2.7%, Netherlands 3.8%, Russia 3.2%, Denmark 2.9% and Italy 1.5%. Import was 21.1 billion Euros in 2023. Main import partners were Finland 6.8%, Lithuania 4.8%, Germany 9.1%, Latvia 2.6%, Sweden 3.8%, Poland 4.6%, USA 3.7% and Italy 2.5%. 55% of Estonia's foreign trade takes place by sea. Therefore year-round maritime connection is essential for trade.

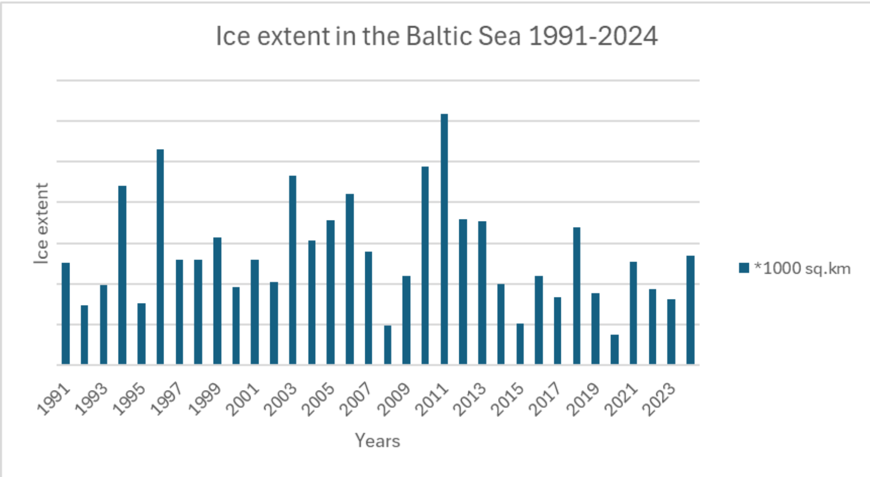
The main Estonian cargo ports – Port of Tallinn, Sillamäe, Kunda, Vene-Balti, and Paldiski North – are located along the northern coast of Estonia. Other significant ports, including Pärnu and the three harbours of AS Saarte Liinid (Virtsu, Roomassaare, and Heltermaa), are situated on the southwestern coast and major islands. Among these, several ports, such as Heltermaa, Kuivastu, Pärnu, Paldiski South Harbour, Rohuküla, Sillamäe, and the harbours of the Port of Tallinn, are part of the Trans-European Transport Network (TEN-T). The Port of Tallinn is categorized as a core network port, while others belong to the comprehensive network.

Icebreaking services [13] in Estonia covered key ports including Tallinn and Kopli Bay ports, Muuga, Kunda, Sillamäe, Pakrineeme, Paldiski South, Paldiski North, and Pärnu in 2024.

Vessel traffic in Estonia's major ports has remained relatively stable in recent years – 10000 to 11000 vessel movements annually in the period of 2020 to 2023 [3].

2.2. Ice conditions in the Baltic Sea waters

The maximum ice extent of the Baltic Sea on winters 1991–2024 varied from 37 000 km² to 309 000 km² (Graph 1). The average maximum of the thirty year period is 141,000 km². The sea ice extent calculated from the ice charts is indicated to the nearest thousand square kilometres. The area of the ice extent indicates sea surface where at least 1/10 is covered by ice. The total area of the Baltic Sea is 420,000 km² [6].



Graph 1 The maximum ice extent in the Baltic Sea

Source: Compiled by authors based on data [6]

The ice season in Estonia generally begins in late December with earlier ice formation in enclosed regions like Väinameri and Pärnu Bay. In contrast the open waters of the Gulf of Finland and Gulf of Riga experience later ice formation and shorter ice seasons lasting 40 to 60 days on average. The eastern Gulf of Finland has the longest ice seasons often exceeding 120 days while enclosed areas such as Pärnu Bay also exhibit persistent ice cover for over 100 days.

Ice thickness varies significantly across regions. Around Estonia's coast average ice thickness is approximately 10 cm, except for Pärnu Bay where it reaches 15 cm. Maximum ice thickness in the northeastern Gulf of Finland can exceed 80 cm during cold winters whereas open areas typically experience thinner ice.

2.3. Icebreaking Fleet in Estonia

The state icebreaking fleet consists of the vessels Tarmo, EVA-316, and Botnica, see Table 1. Botnica is owned by TS Shipping (a subsidiary of the Port of Tallinn) and operates under a charter contract with the state [4]. The multi-purpose/icebreaking vessel Sektori is also employed for these operations. Tarmo and Botnica primarily serve ports along the northern coast while EVA-316 operates in the Gulf of Riga and Pärnu Bay. Sektori, is primarily used in lighter or port-level operations. There are no icebreakers exclusively assigned to the Moonsund and Archipelago regions.

Table 1 Ice breaker technical data [5]

Parameter	Tarmo	EVA-316	Botnica
Year of Built	1963	1980	1998
GT	3916	907	6370
Deadweight, t	1585	266	2890
Length, m	84.5	57.9	96.7
Beam, m	21.2	12.2	24.0
Draft, m	7.4	3.8	7.8
Main Engine, kW	10120	3 × 1717	12 × 1258
Speed, kn	15.5	12	16.5kn/8kn(ice)
Crew	33	13	19 – 23

In addition to state operations private companies contribute to icebreaking with ice-classed vessels. Examples include Alfons Hakans, which operates 1A-class ice-class tugs in multiple ports (e.g., Sillamäe, Kunda, and Paldiski), and the Port of Kunda with its tug Kunda. Similarly companies such as TS Vessels and Kihnu Veeteed operate ice-classed passenger ferries serving Estonia's islands, while Tallink, Viking Line, and Eckerö Line deploy ice-class ro-ro vessels for ferry routes from Vanasadam and Muuga.

Botnica has a DP3 dynamic positioning capability, enabling precise manoeuvrability in both open sea and ice-covered waters. She is classified as ICE-10/ICE-1A* and is capable of continuous operations in ice up to 1.2 meters thick. Botnica is powered by a diesel-electric propulsion plant (see Table 2) with total power of 15 MW for propulsive and auxiliary power and a towing winch rated for 210 tons of brake holding power.

Table 2 Botnica propulsion system [16]

Component	Specification
Stern thrusters	2×ABB Azipods 5000 kW each
Bow thrusters	3×Brunvoll 1150 kW each
Diesel main engines	12×Caterpillar 3512B 1250 kW/1500rpm
Main generators	6×ABB Industries AMG 560 4L 2850 kVA / 3.3kV / 50Hz
Emergency generators	Caterpillar 3406 230kW/ 1500 rpm SR4B 250 kVA / 400V / 50Hz
Switchboards	ABB Industries MH12M 2×2000kVA/3300/400V/50Hz 2×200kVA/400/230V/50Hz

Altogether 12 Caterpillar V 12-cylinder 3500 series high speed engines are producing the diesel power. The engines - each with a maximum continuous rating of 1,257 kW at 1500 rpm - are arranged in pairs sandwiching a common 2 850 kVA ABB alternator which generates power at 50Hz/3.3kV. The six double driven gensets are powering twin 5 MW Azipod propulsors which are rotatable 360 degrees. The Azipod propulsors incorporates an electric motor coupled to a fixed pitch propeller of diameter 3,8 m. In addition, the ship is equipped with three tunnel thrusters in the bow which are important especially in dynamic position operations. Figure 1 illustrates the MSV Botnica and its Azipod propulsion units. The Azipod concept is renowned for its effectiveness in ice-going ships and has proven to be ideal for dynamic positioning operations confirmed by the ABB extensive long term study of ice load measurements onboard the vessel. Global loads acting on the Azipod were measured using strain gauges installed inside the Azipod unit.

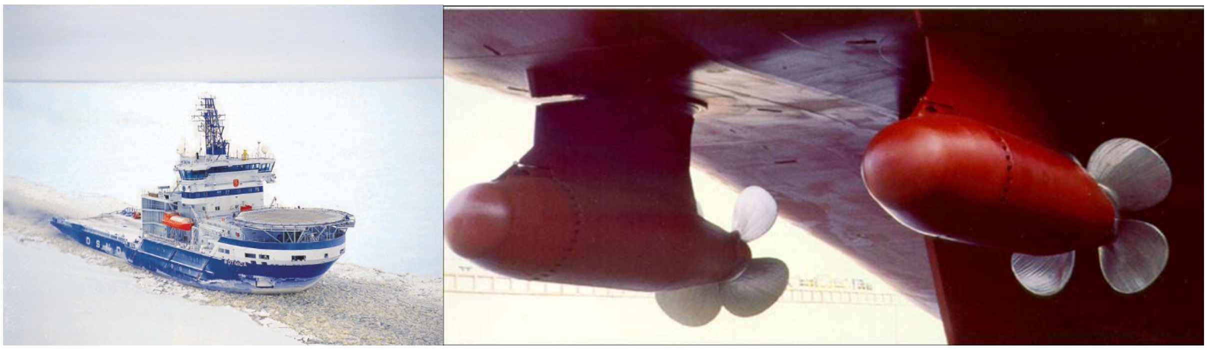


Figure 1 MSV Botnica and Azipod units

Source: [16]

These measurements confirmed the stochastic nature of ice loads and verified that the dimensioning criteria for the Azipod units on Botnica have a clear margin for icebreaking operations in the Baltic Sea.

2.4. Winter Navigation Simulation Framework

The Estonian WNS simulation framework, developed using Anylogic® and based on Kulkarni et al. (2022) [11], adopts a multi-level architecture comprising two independently functioning layers: (i) Environment and (ii) Traffic Flows. The Environment layer captures ice and geographic characteristics such as thickness, concentration, and equivalent thickness while the Traffic Flows layer simulates vessel and icebreaker movements using historical AIS records. These layers are connected via vessel specific h-v curves that determine speed in ice as a function of power and ice thickness [12].

The framework integrates discrete event and agent based modelling. Ice conditions are mapped on a latitude-longitude grid with each cell acting as an agent that updates daily. Vessels and icebreakers are modeled as agents navigating the ice field using state charts adjusting their behaviour dynamically. Visualizations of equivalent ice thickness employ a gradient of blue where darker tones represent thicker ice [14].

Decision-making for icebreakers focuses on reducing vessel waiting times within defined operational zones. Vessel routes derive from historical AIS data while icebreaker movements respond to runtime conditions. Assistance is triggered when a vessel's speed drops below 3 knots, with priority given to the ship waiting the longest.

Icebreaker decisions use satellite data and short term forecasts often combining trips to cut delays. The model simplifies this: requests are queued, longest waiting vessels prioritized, convoys considered, and assistance extends to safe waypoints, with updates enabling cross-zone support.

Three Icebreaker (IB) Scenarios are defined (Table 3). These scenarios configure the deployment of four icebreakers across the Gulf of Finland (GoF) and Gulf of Riga (GoR) using two, three, or all four icebreakers. These three scenarios represent different levels of icebreaking capacity reflecting possible future states of resource allocation under operational and budget constraints.

- Scenario IB1 models a minimal deployment with two icebreakers: one in the Gulf of Finland (GoF IB1) and one in the Gulf of Riga (GoR IB). This setup reflects a constrained-resource scenario with basic regional coverage.
- Scenario IB2 adds a second icebreaker in the Gulf of Finland (GoF IB2) enhancing response capabilities during high traffic periods or mild to moderate winters.
- Scenario IB3 includes all four available icebreakers (assuming fourth icebreaker Sektori or other similar function icebreaker, see Section 2.2) covering the entire icebreaking fleet. It represents full deployment suitable for severe ice conditions or peak operational demands.

These configurations were selected based on the Estonian fleet structure, geographic constraints, and historical traffic patterns.

Table 3 Used IB Engine power in the studied future scenarios

Icebreaker	ME, kW	Shaft, kW	IB1	IB2	IB 3
GoF IB1	13000	10000	✓	✓	✓
GoF IB2	9100	7000		✓	✓
GoF IB3	6250	5000			✓
GoR IB	5500	4400	✓	✓	✓

Simulations also consider three winter scenarios (WS) representing mild (WS1), average (WS2), and severe ice conditions (WS3). By combining IB and WS scenarios the framework investigates system performance under diverse operational and environmental conditions. Here we concentrate on the most promising scenario for the future, i.e having two IBs on the GoF (IB1 and IB 2) and one IB on the GoR.

2.5. Baltic Sea ice season 2023/2024

The 2023/2024 ice season was long beginning early and ending later than usual in most regions although overall ice extent remained around average. The first ice appeared in Tornio on 22nd of October, and by late November, icebreakers in the Bay of Bothnia were already operational, with Kontio beginning icebreaking on 23 November. Assistance restrictions were imposed in Tornio, Kemi, and Oulu the same day.

The Bay of Bothnia became fully ice-covered by 3rd of January about a month earlier than normal. By 21st January the ice covered area had reached 119000 km^2.

The season's peak was on 12th of February with a maximum ice-covered area of 135,000 km^2 (Figure 2). All Finnish icebreakers were active, distributed across the Bay of Bothnia, Bothnian Sea, and Gulf of Finland.

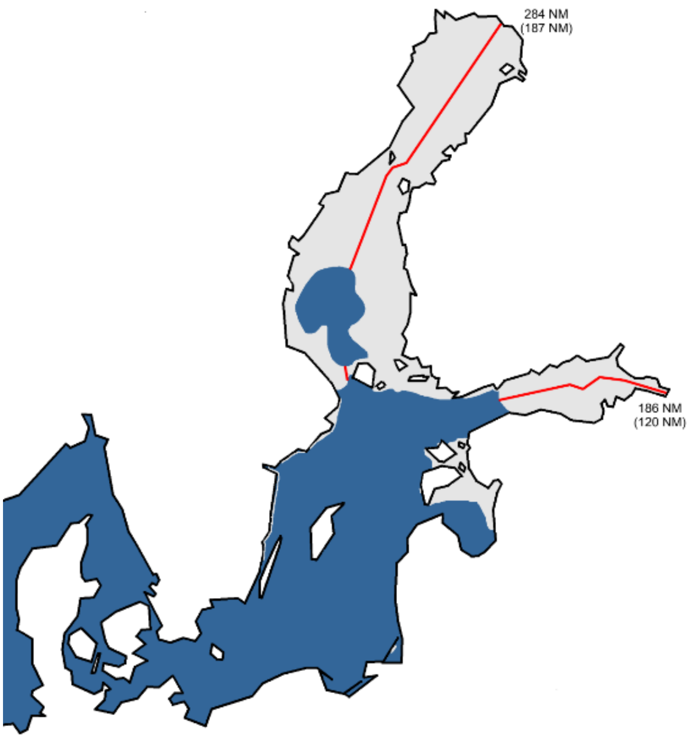


Figure 2 The largest ice area of the season 2024

Source: [6]

The Bay of Bothnia retained drift ice into May, with the final restrictions lifted from Kemi and Tornio on 30 May. Otso returned to Helsinki on 31 May, and the Baltic Sea became fully ice-free on 4 June.

Regionally, the Bay of Bothnia, Quark, and northern Bothnian Sea saw both earlier starts and later ends to the season, along with above-average ice days. In contrast the southern Bothnian Sea and parts of the Gulf of Finland experienced shorter seasons and fewer ice days. Maximum fast ice thickness ranged from 40 to 80 cm in the Bay of Bothnia, 20 to 55 cm in the Bothnian Sea, and up to 60 cm in the Gulf of Finland. On 12th February, vessels from Kemi and St. Petersburg faced navigation distances of 284 and 186 nautical miles to the ice edge, respectively.

Further section presents the comparative results of using ammonia and methanol in various icebreaking deployment scenarios, with a focus on fuel consumption, emissions, and economic performance.

3. FUEL CONSUMPTION ANALYSIS

3.1. Icebreaker scenarios

One of the primary KPIs for icebreaker assistance is the average waiting time per assisted ship, representing how long merchant ships wait for icebreaker assistance. Additional outputs include icebreaker operation time and corresponding fuel consumption (Table 4). According to [12] ships needing icebreaker services must submit requests via their agent or directly through the shipowner at least 12 hours before departure or 24 hours before arriving at the designated meeting point. Average waiting time in IB Scenario 1 is from approximately 130 minutes in for WS1 to more than 1000 minutes for WS3, in IB Scenario 2 110 minutes for WS1 and 400 minutes for WS3 and respectively in IB Scenario 3 110 minutes for and 150 minutes for WS3.

Table 4 IB Scenario 2 Results (3 Icebreakers)

Icebreaker	Time in System (h)	Fuel (MDO) Consumption (t)
WS1		
GoF IB primary	4.5	7.2
GoF IB secondary	38.3	61.6
GoR IB	0	0
WS2		
GoF IB primary	318.2	511.7
GoF IB secondary	273.9	303.2
GoR IB	171.7	124.5
WS3		
GoF IB primary	532.3	856.0
GoF IB secondary	302.5	334.9
GoR IB	235.8	170.9

These values are used to simulate and compare methanol and ammonia consumption as well as to estimate the associated fuel costs under each scenario.

3.2. Environmental regulations

In 2018 the IMO set a goal to cut shipping's GHG emissions by 50% by 2050, updated in 2023 to net-zero by 2050, with interim targets of 30% by 2030 and 80% by 2040, and a commitment to adopt zero/near-zero GHG fuels by 2030 [9]. The EU's "Fit for 55" package complements this by including shipping in the EU ETS from 2024 and introducing FuelEU Maritime which mandates a 2% GHG intensity cut in fuels by 2025 rising to 80% by 2050 (relative to 2020) [2].

IMO's EEDI (2011) set efficiency benchmarks for new ships [7] while EEXI (2021) extended similar requirements to existing fleets [8] alongside the CII which targets operational efficiency [7]. The EU ETS enforces emissions control through allowance surrender or penalties [2] with a temporary 5% compliance relief for ice-strengthened ships in icy waters valid until 2030 [2].

FuelEU and ETS incentivize low-emission technologies via pricing mechanisms, and the IMO aims to globally harmonize regulations by 2027 [9] addressing regional disparities and advancing measures like carbon capture and zero-emission port stays.

3.3. Alternative fuels

Alternative fuels are needed to decarbonizing icebreaking operations. Methanol and ammonia emerging as the promising candidates. Methanol especially when produced from renewable biomass or green hydrogen (e-methanol), offers substantial GHG reductions and is compatible with existing engine systems due to its liquid form. Its main limitation is lower energy density, which requires increased storage capacity and may reduce operational space.

Ammonia presents a longer term option aligning well with net-zero goals due to its carbon-free combustion. However its adoption is constrained by safety concerns and the need for specialized infrastructure particularly under Arctic conditions. Its feasibility for extended missions such as MSV Botnica's summer operations between Estonia and Alaska remains limited due to refuelling constraints [5].

To assess the practical feasibility of alternative fuels in maritime decarbonization, a stakeholder workshop was conducted as part of the EU Horizon project "Twinning to enable Baltic Sea maritime transport meet Fit–for–55 regulations (Baltic Fit)". The workshop brought together over 50 representatives from shipping, port operations, shipbuilding, and maritime services to evaluate methanol and ammonia as alternatives for future maritime operations. Table 5 summarizes the main advantages and challenges of both fuels based on stakeholder insights and technical assessments updated by authors with specifics of cold environment.

Table 5 Comparison of ammonia and methanol as marine fuels for Arctic operations

	Ammonia	Methanol
Environmental Benefits	Close to zero carbon emissions	Lower carbon emissions and reduction of SOx, NOx, and PM.
	Can be produced from renewable energy sources like wind and solar.	
	Blue or grey methanol/ammonia generates higher carbon emissions calculated well to wake	
	Liquid ammonia generates sea pollution if spilled, destroying marine organisms.	
	Combustion avoids CO_2 emissions even in cold environments.	Effective emissions reduction remains valid in Arctic air quality zones.
Infrastructure Requirements	There is already a widespread storage and delivery system for ammonia.	Commercially ready with available supply infrastructure.
	Lack of bunkering and bulk infrastructure needed along shipping routes.	
	Requires development of Arctic compliant bunkering systems resistant to freezing and leakage under sub-zero conditions.	Liquid state at ambient pressure simplifies Arctic handling and storage reducing insulation demands.
Technical Feasibility	Can be used in various combustion engines and fuel cells.	Compatible with different marine engines.
	Can be stored at lower pressures and higher temperatures than liquefied hydrogen and LNG.	High energy density.
	Can be used in marine engines as blended with other fuels	
	Ammonia has a higher volumetric energy density than hydrogen.	.
	Due to ammonia's high ignition temperature and low flame speed, cold ambient conditions may impair ignition and combustion stability unless engines are equipped with optimized cold-start and thermal control systems.	Engines perform reliably in cold weather, fuel system pre-heating may be used to support cold starts and maintain thermal stability, even though viscosity remains low at Arctic temperatures.
Economic Viability	Produced from natural gas emits higher GHG emissions than LNG, HFO and MDO.	
	Costs are currently higher than fossil fuels	
		Wider adoption of methanol is subject to economic viability and carbon credentials.
		Methanol's low calorific value compared to MDO and HFO can result in higher fuel costs.
Operational Challenges	Ammonia is highly toxic, requiring additional safety measures and higher costs.	Methanol is required additional fire safety protection.
	Ammonia remains liquid under pressure but boils at –33.1 °C, requiring insulated and pressurized storage to prevent vaporization in Arctic conditions. Lower flammability reduces fire risk, but high toxicity and corrosiveness increase handling and safety system complexity.	Methanol remains liquid at -97.6°C, less freezing risks in Arctic operations, simplified fuel logistics in remote winter ports. Lower toxicity and flammability reduce safety system complexity vs ammonia.

Compared to marine diesel oil (MDO) which remains cost effective and proven in cold climates methanol and ammonia incur higher costs but offer significant environmental advantages. Current price estimates [1] vary significantly depending on the production method. Grey methanol produced from natural gas is priced between USD 15 to 30 per GJ (roughly USD 300 to 600 per ton). Green methanol synthesized from renewable hydrogen and captured CO_2 is ranging from USD 40 to 80 per GJ (USD 800 to 1600 per ton). Grey ammonia (fossil-based) generally costs between USD 15 to 25 per GJ and green ammonia produced via electrolysis and nitrogen fixation ranges from USD 30 to 50 per GJ. MDO remains at approximately USD 15 per GJ. Long term methanol forecasts (2030 to 2050) range from USD 20 to USD 55 per GJ.

4. ASSESSING METHANOL AND AMMONIA AS A FUEL FOR THE ICEBREAKER BOTNICA SIZE VESSEL

4.1. Selection of the engine prototype

The Wärtsilä 32 Methanol (W32M) engine was selected as a prototype for retrofitting Botnica due to its flexibility, high performance, and alignment with sustainable shipping objectives. The W32M is a medium-speed, 4-stroke engine capable of running on methanol as a primary fuel while also supporting operation on conventional fuels such as MDO or heavy fuel oil (HFO).

The W32M engine has been optimized to meet stringent emissions regulations including compliance with IMO Tier III standards when equipped with selective catalytic reduction technology. Methanol operation offers substantial environmental benefits including significantly reduced SOx and particulate emissions, while NOx emissions are reduced by up to 50% compared to conventional marine fuels.

The technical configuration chosen for Botnica includes 4 × 6L32-M engines [17]. Each engine features six cylinders with a total power output of 13920 kW (4 × 3480 kW) delivering the performance required for Botnica's demanding icebreaking operations. The engines operate at 750 rpm with a cylinder bore of 320 mm and a stroke of 400 mm ensuring optimal combustion efficiency across various load ranges. Additional key parameters include a mean effective pressure of 21.3 bar and a maximum exhaust gas temperature of 430°C reflecting the engine's high efficiency and operational reliability.

Methanol's properties make it particularly suitable for Botnica's operations. It has simpler storage and handling requirements compared to LNG which reduces retrofit complexity and associated costs. The incorporation of the Wärtsilä MethanolPac system further enhances this compatibility by providing an integrated solution for methanol fuel supply. MethanolPac includes essential components such as a Low-Pressure Pumping System (LPPS), Methanol Fuel Preparation Unit (MFPU), and advanced control systems. These systems ensure safe and efficient methanol handling, with redundancy and safety features such as inert gas systems to minimize explosion risks.

To support methanol operation the Wärtsilä Methanol Pac system includes the following components:

- LPPS ensures safe and efficient fuel transfer from methanol storage tanks to the MFPU,
- MFPU conditions the fuel for engine injection by maintaining precise pressure and temperature levels,
- Control Systems provide real-time monitoring and redundancy, ensuring safety during operations,
- Inert Gas System maintains a non-flammable environment within the fuel tanks to prevent explosion risks.

In parallel ammonia is considered using the Wärtsilä engine which was tested in Stord, Norway during 2022-2023 – 4-stroke marine engine optimized for ammonia.

This engine supports full ammonia combustion with minimal pilot fuel and incorporates dedicated safety and emissions systems including

- Ammonia fuel supply system,

- Ammonia Release Mitigation System,
- NOx Reducer.

These systems are essential to safely handle ammonia's toxicity and to minimize NO_X and potential N_2O emissions.

For ammonia a configuration of 4 × Wärtsilä 6L34DF engines, each engine features six cylinders with a total power output of 12000 kW (4 × 3000 kW).

4.2. ASSESSMENT OF OPERATIONAL COSTS WITH METHANOL OR AMMONIA AS A FUEL

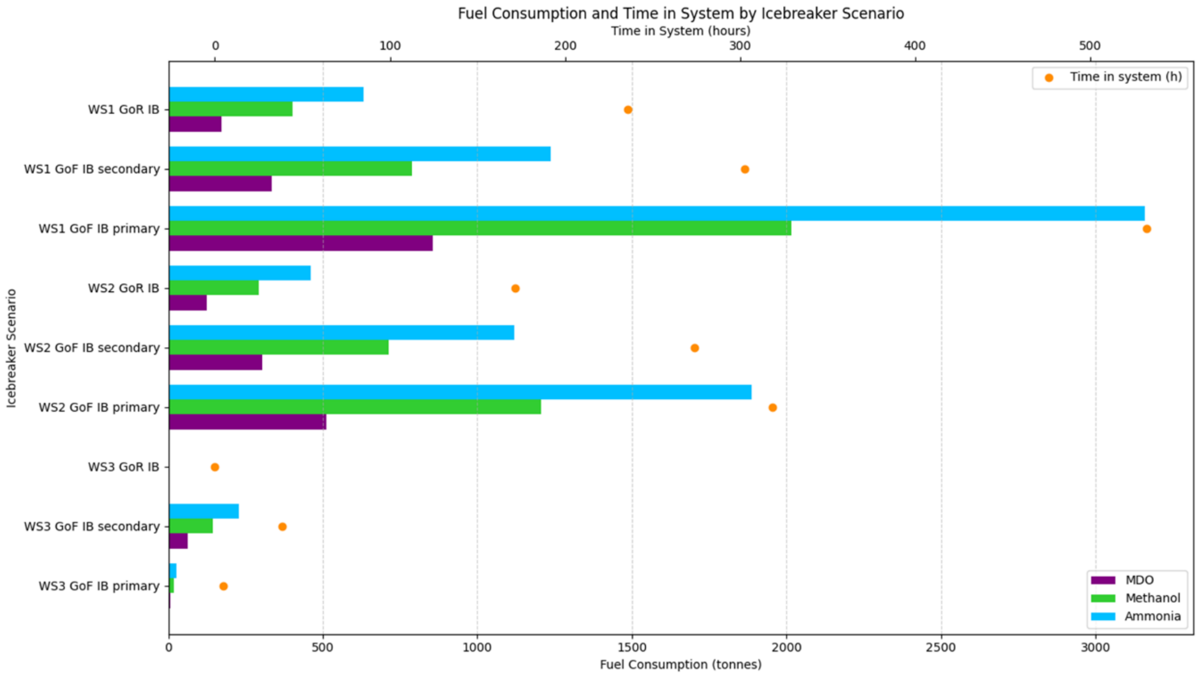
To evaluate the performance of the W32M engines the research involves modelling and simulation under typical operational conditions. These include fuel consumption rates during icebreaking, port stays, and laid-up periods, as well as emissions performance across varying power loads as shown in Graph 2 for MDO, methanol and ammonia case. The fuel consumption values used for this assessment are derived from the WNS to simulate realistic operations. For example, in IB Scenario 2 under WS2, the Gulf of Finland's primary icebreaker is estimated to consume 511.7 tons of MDO, rising to 856.0 tons under WS3. These values serve as the baseline for energy based calculations to methanol and ammonia equivalents.

Methanol offers considerable efficiency with energy consumption ranging between 7102 to 7251 kJ/kWh across different loads [17]. The fuel flexibility of the engine allows operation on either low-sulphur fuel oil (LFO) or methanol with specific fuel consumption remaining competitive at partial loads (Table 6).

Table 6 Fuel consumption for various methanol fuels [17]

Parameter	Load, %	Value, g/kWh
LFO	100	187.9
	85	185.2
	75	185.1
	50	192.2
Parameter	Load, %	Value, kJ/kWh
Pilot Fuel Methanol	100	705.7
	85	772.4
	75	899.0
	50	1325.7
Energy Methanol	100	7261
	85	7251
	75	7102
	50	7136

Methanol's energy density (approx. 19.9 MJ/kg) is significantly lower than that of MDO (42.6 MJ/kg). This disparity means that methanol consumption must be higher to deliver the same energy output. To estimate methanol consumption for icebreaking scenarios we adjust for this energy difference and account for the efficiency of methanol engines which is typically 90% of MDO engine efficiency. Ammonia's energy density is even lower (approx.12.7 MJ/kg) which results in a significantly higher fuel mass requirement compared to both MDO and methanol. To model ammonia consumption in icebreaking scenarios it is assumed that ammonia engine efficiency also in the range of 90% relative to MDO.

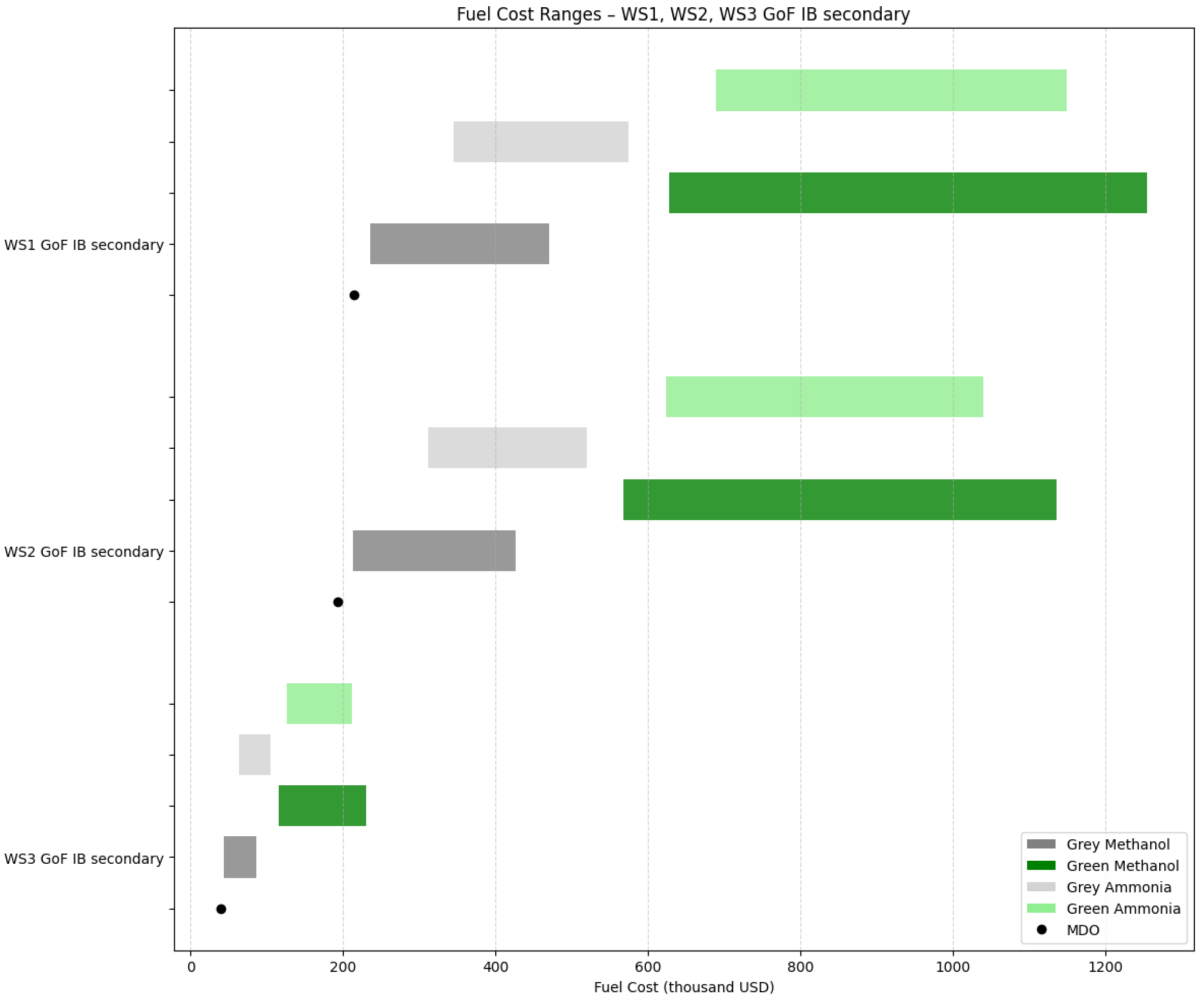


Graph 2 The IB Scenario 2 results with MDO, methanol and ammonia as a fuel vs time in system during different scenarios

Source: Compiled by authors

The results indicate that methanol consumption in tons is approx. 2.5 times and ammonia consumption is approx. 3.7 times higher than MDO in all scenarios. For example, in WS2 the primary icebreaker in the Gulf of Finland consumes 512 tons of MDO whereas the equivalent ammonia requirement would be 1888 tons.

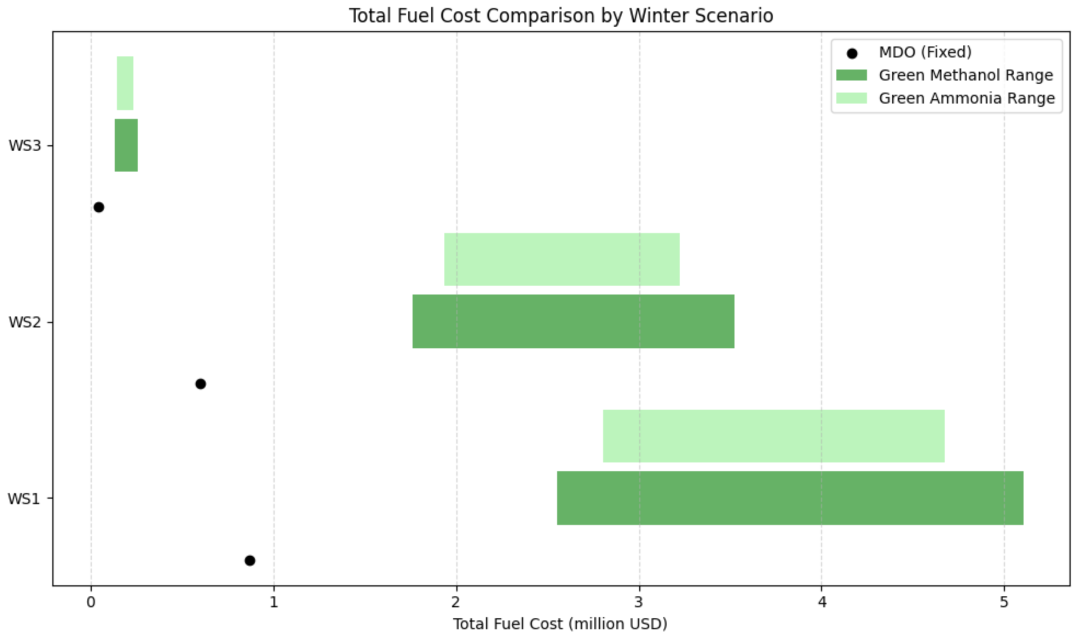
Graph 3 presents the estimated operational costs under different winter conditions. The calculations use estimated methanol and ammonia current price range. Fuel cost comparisons show a significant increase when switching to low carbon alternatives. For example, in the WS1 Gulf of Finland IB secondary scenario operating with green methanol costs between USD 628,000 and 1.26 million. Green ammonia ranges from USD 690,000 to 1.15 million, compared to approximately USD 214,000 for MDO. These differences are visualized also in Graph 4.



Graph 3 Fuel costs with MDO, methanol and ammonia as a fuel

Source: Compiled by authors

Total fuel costs were calculated for all icebreakers participating in WS1, WS2, and WS3 with MDO, grey and green methanol, grey and green ammonia, including their price range. For example, in WS1 the total cost using MDO was approximately USD 870,000, the cost with green methanol ranged from USD 2.55 million to USD 5.11 million, and with green ammonia from USD 2.80 million to USD 4.67 million. This means that fuel costs with green methanol was 2.9 to 5.9 times more expensive and with green ammonia 3.2 to 5.4 times more expensive than MDO under current fuel price assumptions.



Graph 4 Fuel costs with MDO, methanol and ammonia as a fuel by Winter Scenario

Source: Compiled by authors

Although IMO and EU climate regulations increasingly favour low-carbon fuels the higher fuel consumption and operational costs associated with methanol necessitate further improvements in engine efficiency, fuel storage solutions, and potential policy incentives to make methanol a financially viable option for icebreaking fleets.

4.3. Implementation Barriers and Risk Considerations

Several key barriers limit immediate implementation of methanol and ammonia. First, fuel availability and infrastructure remain limited. Methanol bunkering infrastructure is still emerging and ammonia even more widely used industrially lacks marine grade storage and transfer systems adapted for Arctic conditions. Investment in fuel handling, safety systems, and cold weather insulation is critical. Second, retrofitting and safety risks pose challenges. Ammonia's toxicity demands specialized ventilation, leak detection, and crew training protocols that increase both capital and operational expenditures. Methanol is less toxic but still flammable, requiring ignition control and monitoring systems. Third, economic uncertainty around fuel prices and carbon credit schemes affects investments. Green methanol and ammonia remain significantly more expensive than MDO. Policy incentives such as carbon pricing, tax exemptions, or subsidies may be required to offset these costs. Fourth, technology readiness is uneven. Large scale ammonia engines are still under pilot testing, and long-term durability in icebreaking operations is unproven. To overcome these barriers phased implementation strategies, pilot projects in controlled routes, and public private partnerships will be essential. But regulatory development, fuel supply chains, and vessel design innovations will ultimately determine the pace and success of fuel transition in the icebreaking sector.

5. CONCLUSION

The study assessed the feasibility of using methanol and ammonia as fuels for icebreaking operations in the Northern Baltic Sea, focusing on the WNS and the icebreaker Botnica as a reference vessel. A system-level simulation was conducted across three winter severity scenarios (mild, average, and severe), using operational data from IB Scenario 2 which includes two icebreakers in the Gulf of Finland and one in the Gulf of Riga. The analysis incorporated climate-related changes in ice conditions and compliance with EU and IMO regulatory frameworks.

The simulation results showed that replacing MDO with methanol or ammonia significantly increases fuel capacity requirements due to lower energy density and combustion efficiency. In IB Scenario 2 under average winter conditions WS2 the Gulf of Finland's primary icebreaker required 511.7 tons of MDO. In energy equivalence this would translate into approximately 1,275 to 1,325 tons of methanol or 1,880 to 1,900 tons of ammonia.

The cost implications are substantial. In WS1 operating the secondary Gulf of Finland icebreaker under IB Scenario 2 with green methanol projected to raised fuel costs from approximately USD 214,000 (MDO) to USD 628,000 to 1.26 million. The same operation using green ammonia cost between USD 690,000 and 1.15 million. Total fuel costs for all icebreakers in WS1 rose from USD 870,000 (MDO) to USD 2.55 to 5.11 million (methanol) or USD 2.80 to 4.67 million (ammonia) depending on fuel price assumptions.

A key limitation of this study lies in fuel pricing uncertainty. The cost figures provided are indicative reflecting current price estimates and should be interpreted in the context of future fluctuations driven by carbon pricing, fuel production methods, and regulatory incentives. This analysis does not account for potential costs associated with GHG pricing mechanisms, such as carbon credits under the EU Emissions Trading System or future fees introduced by the IMO or other regulatory bodies.

Methanol is technically viable in the short term due to engine compatibility and ease of retrofitting. Ammonia offers long term promise but remains constrained by toxicity and safety requirements. Both fuels require significant infrastructure development and onboard system adaptation. It will be essential to align environmental goals with cost-effective implementation for achieving sustainable maritime transport in ice-covered regions.

Further research should focus on propulsion system adaptation, fuel logistics in remote ports, and policy design to improve the financial feasibility of alternative fuels in icebreaking operations.

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TRANSFORMATION OF MARITIME LOGISTICS AND SUPPLY CHAINS IN MODERN GEOPOLITICAL CHALLENGES (STRATEGIC ROLE OF GEORGIA)

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Abstract

Contemporary geopolitical and economic shocks have significantly impacted maritime logistics and the structure of global supply chains. The war launched by Russia in Ukraine, the acute economic consequences of the pandemic, security risks associated with navigation in the Red Sea, and frequent distractions to ship traffic in sea channels have led to significant changes in both the geographical location of strategic industrial complexes and the structure of the supply chains that support them. As a result, specific countries and companies are gradually moving to diversified supply chain models. The purpose of the presented article is to analyse the main trends in the transformation of maritime logistics and supply chains and to assess the role and opportunities of Georgia in the new geo-economic context. The study pays special attention to assessing the competitiveness of ports in the Black Sea region, for which cargo turnover and throughput indicators, investment dynamics and infrastructure development trends are used. The paper applies mixed research methods that gives us the possibility of both quantitative data analysis and the assessment of structural and regional trends. The study is based on the three main analytical approaches – statistical data analysis (analysis of cargo turnover and throughput utilization indicator of Georgian ports), empirical data analysis (the infrastructure capabilities of ports and volume of carried out investments are studied) and comparative analysis (comparative analysis of supply chain models and transport corridors). Additionally, document analysis and SWOT analysis are used. The research results demonstrate the context of global transformation, where Georgia possesses a strategic maritime transport and logistics potential of international and regional importance. The results of the article are important both in terms of theoretical understanding of the processes taking place in supply chains and maritime logistics at the global and regional levels, and in terms of implementing effective state policy in this area

Keywords: Maritime Logistics, Supply Chain, Seaports, Cargo Turnover, Competitiveness, Transformation

1. INTRODUCTION

Maritime logistics and supply chains are the main structural means of the global economic system. Their effective operation has a significant impact on the pace and trends of international trade and regional economic integration, as well as on individual countries' economic stability and competitiveness.

The goal of the presented research is to comprehensively analyse the processes of large-scale transformation of maritime logistics and supply chains, which are influenced by the modern, highly dynamic and uncertain geopolitical environment and many global challenges. In specific, the research aims to evaluate the potential role and importance of Georgia in this context, to reveal the prospects and consequences that the country has in terms of the development of regional and international logistics networks.

Thus, the study defines in detail the strategic directions and priority steps, the consistent development of which will play a significant role in establishing Georgia as a regional transport and logistics centre and its integration into the global supply network. It emphasises what specific actions are needed to fully realize the country's transit potential and increase its competitiveness in international transport corridors.

2. LITERATURE REVIEW

2.1. Maritime Logistics and Supply Chain Transformation

Maritime logistics is one of the most vital and strategic components of the global logistics system, which includes the transportation of commodities using maritime routes, the smooth operation of port infrastructure and the effective coordination of multimodal transit networks. This component is closely related to the development of international trade and the processes of deepening economic integration, especially when it comes to the optimal, timely and safe transportation of large volumes of cargo.[13]

A supply chain is a system of coordinated and integrated processes for transporting flows of goods, services, information, and financial resources from the primary source to the final consumer (Mentzer et al. 2001, 4). The effectiveness of supply chains is assessed by three main criteria: timely delivery, flexibility, and sustainability.

Recent crises – COVID-19, the Russia-Ukraine war, shipping disruptions in the Red Sea, and energy fluctuations – have exposed the shortcomings of traditional, centralized supply models: shortages of supplies, increased delivery times, and logistics costs. [3],[10] These challenges have put on the agenda the need for a fundamental transformation of supply chains and logistics, which involves structural changes, optimization of existing models, and the introduction of so-called "flexible-hybrid models". [6],[12] The COVID-19 pandemic, the conflict in Ukraine, the Houthi attacks in the Red Sea, and the sinking of a ship in the Suez Canal have starkly demonstrated the vulnerability of global supply chains. Many companies have been forced to rethink their strategies and switch to a new, more risk-oriented model – Just-in-Case.

For example:

- Electronics manufacturers have begun to purchase components locally or regionally (for example, TSMC, Samsung, Intel - their new factories in the USA and Japan).
- Large retail chains (e.g. Amazon, and Walmart) have significantly increased warehouse volumes in regions where the risk of supply disruptions was high.
- Automakers (Toyota, BMW, Ford) have revised their inventory strategies to reduce their dependence on global frameworks.

All this indicates that future supply chains will be based more on sustainability and adaptability than on extreme optimization.

Table 1 Comparative analysis of JIT vs. JIC models

Criteria	Just-in-Time (JIT)	Just-in-Case (JIC)
Inventory level	Minimum	High
Dependence on supply	High – the product must arrive on time	Less – Stocks provide a buffer
Efficiency	Optimal - in terms of costs	Less cost-effective
Sustainability in times of crisis	Low	High
Trend after 2020	Downward	Upward

Source: Statistical data was analysed by the authors. (Batumi 2025)

2.2. Supply Chain Diversification Strategies

Against the backdrop of global crises, the trend that economists have referred to as the strategy of "short supply chains" is becoming active. Companies and states try to move production chains to geographically close areas (nearshoring, friend-shoring) to protect their economic interests.

In this context:

- EU countries are increasing their share of production in the domestic market, especially in energy and technology critical sectors.
- The US initiated the CHIPS and Science Act, which aims to domestically manufacture semiconductors.
- Asian countries (for example, Vietnam and Indonesia) actively attract companies that try to move production networks from China.

In response to systemic shocks, the literature identifies three strategies for diversifying supply chains.[16]

1. Geographic diversification – development of alternative transport corridors with a central manufacturer.[11]
2. Technological diversification – integrated management of multimodal transport based on digital platforms. [14]
3. Institutional diversification – decentralization of decisions and strategic allocation of risks.[12]

2.3. Georgia and the geoeconomic potential of the “Middle Corridor”

The “Middle Corridor,” which is considered an alternative route for Eurasian cargo flows, allows the South Caucasus to provide more secure and politically low-risk transportation.[1] The development of Georgia’s ports of Poti and Batumi provides a secure, politically low-risk route between Europe and Asia, although infrastructure constraints and lack of coordination remain major challenges. [7] Georgian researchers have emphasized in various studies the need to develop national and regional maritime transport clusters, which would strengthen Georgia’s competitive potential.[8]

2.4. Summary of the discussion

Existing research shows that traditional centralized supply chains are undergoing a transformation from “cost-minimization models” to “flexible-hybrid and diversified model architectures”. [6],[12] Georgia’s strategic location and “middle corridor” development opportunities create a significant perspective in the context of regional-global supply chains, but this requires strengthening digital platforms, deep involvement of public-private partnerships, and the formation of maritime transport clusters.

3. THE IMPACT OF GEOPOLITICAL CHANGES ON MARITIME LOGISTICS

3.1. Analysis of global and regional processes

The main characteristic trends of the global logistics field are the reassessment of systemic globalization and the strengthening of politically sensitive regionalization. At the current stage, the multi-route, "global-local" networks characteristic of the 2010s are being replaced by a concentration of flexible regional connections (hubs) that better respond to local specificities and political challenges.[11] Both the state and the private sector are involved in the development of maritime and inland logistics corridors in the Black and Caspian Sea regions, which contributes to the revival of historical East-to-West transport routes and their integration into global trade.[16]

3.2. The impact of war, pandemics and security risks

Over the past five years, global logistics networks have faced many serious crises that have caused significant disruptions in the operations of both sea and land transport systems.

During the COVID-19 pandemic, additional port regulations, extended customs procedures and restrictions on the rotation of seafarers have slowed down the timeliness and sustainability of global transport operations, which has had a direct impact on the sustainability of the global economy and the efficiency of supply chains. [3] In the second quarter of 2020, during the peak of COVID-19, container throughput at global ports decreased by approximately 15%, while maritime transit times increased by an average of 30%. [15]

The Russia-Ukraine war, with its blockades and international sanctions in the Black Sea, has complicated the timely and safe delivery of commodities, energy, and industrial cargo, which has become a significant challenge for many countries around the world. These processes have coincided with the activation of alternative corridors and accelerated testing of new transport routes. [10] For example, in 2022, cargo turnover at Black Sea ports decreased by 40%, while delivery times via alternative routes have increased by an average of 20–25 days.[2]

Increased security risks in the Red Sea, including attacks on ships, have forced transport companies to change container routes. As a result, the transportation period has increased, and insurance premiums have increased by 20%, which ultimately led to an additional 10–15% increase in transportation costs. [5]

Such crises clearly show that the stability and flexibility of global supply chains cannot be satisfied only with the operational mechanisms, but require strategic planning, risk management, and the implementation of preventive policies at the international and regional levels.

Table 2 Impact of global crises on maritime logistics and supply chains (2020–2024)

Global crisis	Impact on logistics	Statistical indicators
The COVID-19 pandemic	- Port delays, - Extended customs procedures, - Limitation of crew's rotation	- Decrease in cargo turnover -15% - Increase in transportation time: +30% (UNCTAD 2021)
Russia-Ukraine war	- Blocking of Black Sea routes, disruption of food and energy supplies	- Cargo turnover of - Black Sea ports -40%; - Delivery time increase +20–25 days
Red Sea Crisis	- Increasing number of attacks on ships - Increase in insurance rates - Rearrangement of routes	- Increase in insurance costs: +20% - Increase in logistics costs: +10–15% (ICS 2022)

Source: Statistical data was analysed by the authors. (Batumi 2025)

3.3. New Logistics Corridors and Transportation Routes

The challenges facing global transport networks - war, sanctions and security risks - have given a significant impetus to the search for new, safe and flexible logistics routes. In this process, several strategic corridors have been identified, which today play a crucial role in the formation of new routes and the reorganization of supply networks.

The Middle Corridor (Trans-Caspian International Transport Route – TITR) is a strategic transport alliance that starts in China and crosses the Caspian Sea through Central Asian countries, then passes through the territory of Azerbaijan and Georgia and connects to Europe. In recent years, this route has moved from the status of an alternative corridor to the position of a globally strategic transport line, which is partly due to the obstruction of the corridor by Russia and the sanctions imposed in the wake of the war in Ukraine. The cargo turnover of the Middle Corridor amounted to 586 thousand tons in 2021, and by 2023 it increased to 2.7 million tons, which indicates its growing role (TITR Association 2024). The average time for delivering cargo from China to Europe through this corridor is 12–15 days, which is approximately 30–40% faster than the Russian Northern Route in the post-war period. Despite its growing importance, the Middle Corridor faces challenges such as infrastructure constraints, less coordination of customs procedures, and the need to optimize transit costs.

The India–Middle East–Europe Corridor (IMEC) is a new strategic initiative announced at the 2023 G20 Summit, which aims to develop a logistics route from India through the Middle East to Europe. The project involves significant transport and infrastructure integration through the United Arab Emirates, Saudi Arabia and Israel, which should result in enhanced rail, maritime and energy connectivity between India and Europe. The strategic objective of IMEC is to strategically balance the Northern Sea Routes and China's Belt and Road Initiative. It is planned to develop transport and logistics infrastructure – including ports and railway lines – and lay power cables to connect the energy systems of Europe and India (the project is being implemented in coordination with the European Union, the United States, India and the Gulf countries). It is expected that IMEC will make it possible to reduce the time for cargo transportation between India and Europe by about 40% compared to traditional sea routes. At this stage, the corridor is still in the initial phase of development, but it is already considered one of the priority directions in which large investments are planned.

The North Sea-Baltic Corridor is one of the main directions of the European Union's Trans-European Transport Network (TEN-T), which aims to create a safe and efficient transit alternative for the countries of Central and Eastern Europe, especially in the context of replacing traditional routes via Russia. The corridor connects the Baltic states (Latvia, Lithuania, Estonia) with the North Sea ports via Poland and Germany. The project plans to integrate transport infrastructure, modernize railway routes and develop logistics hubs, which will significantly reduce the transit time of cargo from Eastern Europe to the Benelux region by approximately 20–25%. In 2023, approximately 15% of the EU's freight flows were already moving along this route, which testifies to its growing importance in geopolitically stable and diversified transport networks.[1], [16]

Table 3 Comparative analysis

Corridor	Starting point	Destination	Duration (days)	Cargo turnover (2023)	Status	Difficulties
Middle Corridor (TITR)	China	Europe	12–15	2.7 million tons	Active and growing	infrastructure, customs procedures
IMEC	India	Europe	14–18	in planning stage	in planning process	political-regional stability
North Sea-Baltic Corridor	Baltic States	Benelux	5–8	High	Active within TEN-T	Need for expansion

Source: Statistical data was analysed by the authors. (Batumi 2025)

4. STRATEGIC ROLE OF GEORGIA IN GLOBAL AND REGIONAL SUPPLY CHAINS

4.1. Strategic role of Georgia in global and regional supply chains

Georgia is located on the Eurasian continental bridge, where West and East, North and South meet. The territory of the country is one of the shortest land routes between Europe and Asia, which determines its importance as a transit and logistics hub in the region. This geographical advantage leads to the development of international transport corridors, including Europe-Caucasus-Asia (TRACECA), South Caucasus Railway, Middle Corridor and Poti-Baku-Aktau-China connecting road and freight routes. Moreover, Georgia is the only country in the region that has a free trade agreement with both the European Union (DCFTA) and China, which further increases the investment attractiveness of its logistics capabilities.

In terms of logistics infrastructure, Georgia has important road and rail corridors, including the East-West Highway (E60/E70), the Baku-Tbilisi-Kars Railway, and operational ports on the Black Sea in Poti and Batumi. The construction of the deep-water port of Anaklia has also started. Due to the geopolitical reality, the position of Georgia is also very important for energy logistics, which is reflected in the transportation of oil and gas through pipeline routes (Baku-Tbilisi-Ceyhan and South Caucasus Pipeline), which represent the southern energy corridor and are an alternative direction against the Russian monopoly. Therefore, Georgia's logistics positioning is based not only on geographic advantage but also on its political credibility, strategic policy focused on multilateral trade agreements and infrastructural connections, which makes it possible to transform the country into a regional hub, especially in conditions of growing interest in the Middle Corridor.

4.2. Assessment of Black Sea ports: cargo turnover, capacity and infrastructure

Georgia's Black Sea coast is a critical component of the country's transportation and logistics system, with two major commercial ports - Poti and Batumi - playing a central role in managing international trade and transit flows. In addition, the Anaklia deepwater port project, which is under development, is considered a strategically important asset that will significantly change the regional transportation landscape.

Table 3 presents the values of the parameters for assessing the efficiency of the Poti Seaport, as well as the values of one of the efficiency indicators - the capacity utilization indicator.

Table 4 Values of Poti Seaport efficiency evaluation parameters

		2015	2019	2021	2022	2023
dry cargo	Bandwidth - 20.0 million tons per year					
	cargo turnover	5.9	8.1	6.9	6.6	7.2
	Growth rate of cargo turnover, %	37.3	-14.8	-4.3	9.1	37.3
	bandwidth utilization, %	30	41	35	33	36
liquid cargoes	Bandwidth - 1.0 million tons per year					
	cargo turnover	0.5	0.6	0.5	0.5	0.5
	Growth rate of cargo turnover, %	20.0	-16.7	0.0	0.0	20.0
	bandwidth utilization, %	50	60	50	50	50
containers, TEU	bandwidth - 550,000 TEU per year					
	Cargo turnover, TEU	363 936	531 735	387 368	302 082	357 623
	Growth rate of cargo turnover, %	-	46.1	-27.2	-22.0	18.4
	bandwidth utilization, %	66	97	70	55	65
New Port of Poti						
	Capacity is 1.5 million dry cargo, 100,000 TEU and 30,000 barge cargo[1]					

Source: National Transport and Logistics Strategy of Georgia for 2023-2030. Statistical data was analysed by the authors. (Batumi 2025)

[1] https://mta.gov.ge/uploads/other/NEWSLETTER_-_MTA_1.pdf

The Port of Batumi specializes in handling oil products, liquid and dry cargo. Its annual throughput capacity is approximately 5 million tons. Table 4 presents the values of the parameters for assessing the efficiency of individual terminals of the Batumi Sea Port.

Table 5 Values of indicators for evaluating the efficiency of the Batumi Sea Port

		2015	2019	2021	2022	2023	2024
Oil terminal	Bandwidth - 15 million tons per year						
	Cargo turnover, million tons	4.5	0.9	1.2	1.5	2.0	1.6
	Growth rate of cargo turnover, %	-	-80.0	33.3	25.0	33.3	-20.0
	bandwidth utilization, %	30	6	8	10	13	11
Dry cargo terminal	Bandwidth - 2.7 million tons per year (including ferry loads)						
	Cargo turnover, million tons	1.203	0.695	0.913	1.211	1.742	1.942
	Growth rate of cargo turnover, %	-42.2	31.4	32.6	43.8	11.5	-42.2
	bandwidth utilization, %	45	26	34	45	65	72
Container terminal	Bandwidth - 350 000 NO per year						
	Cargo turnover, TEU	61 980	116 081	103 302	99 187	119 471	109 000
	Growth rate of cargo turnover, %	87.3	-11.0	-4.0	20.5	-8.8	87.3
	Bandwidth utilization, %	18	26	30	28	34	31
Total	Capacity - 180,000 passengers per year						
	Passenger	-	-	-	-	-	-

Source: National Transport and Logistics Strategy of Georgia for 2023-2030. Statistical data was analysed by the authors. (Batumi 2025)

Seaport performance indicators reveal that the capacity utilization rate of individual terminals is very low. Anaklia Port - the planned deep-sea port is a long-term strategic project of the country. Its main advantage will be the ability to receive Panamax and Super Panamax vessels, which will ensure a significant increase in cargo turnover (first phase - 8 million tons per year) and the integration of the country into global ocean networks. Georgia is actively working to modernize the infrastructure of Black Sea ports in cooperation with partners and attracting investments. In 2024, the construction of a deep-water terminal by a company associated with the Maersk group began in the port of Poti, and the activation of the Anaklia project creates the basis for strengthening the regional importance of the country's port system in the context of the middle corridor.

4.3. Investment dynamics and trends in logistics infrastructure

The logistics sector of Georgia has become one of the most active investment areas in recent years, which is due to the country's strategy to become a regional transport hub. Investment growth is particularly noticeable in Black Sea ports, railways, warehousing infrastructure, and the development of digital platforms.

Main directions:

- Port infrastructure. In 2024, 250 million US dollars were invested in the construction of the Poti deep-water terminal. The cost of the first phase of the port of Anaklia is estimated at 600 million dollars, and the full development requires a budget of up to 2.5 billion dollars.
- Modernization of railways. The renovation of the Tbilisi-Batumi line considers an investment of approximately 350 million dollars in 2020-2025, which contributes to the increase in the speed and efficiency of domestic transport. Transit hubs and terminals. More than 100 million private investments have already been made in the development of industrial centers - Rustavi Logistics Center and Tbilisi Dry Port.

- Warehouse and digital logistics. In 2018-2024, the warehouse area was doubled. Digital solutions are being introduced (GPS, custom platforms).

Table 6 Investment growth rates (2015–2024):

Year	Investment ($ million)	Growth (%)
2015	85	—
2018	135	+58.8%
2020	190	+40.7%
2024	310	+63.1%

Source: National Transport and Logistics Strategy of Georgia for 2023-2030. Statistical data was analysed by the authors. (Batumi 2025)

This dynamic demonstrates that Georgia has begun to effectively capitalize on its logistics potential, both within the framework of the Middle Corridor and integration with new global routes (IMEC).

In the below table, we have analysed the main aspects of the SWOT. Strengths are: Georgia's key advantages are its strategic geographical location as a transit bridge, Weaknesses: Key weaknesses include certain infrastructure limitations. Opportunities: Global changes are creating new opportunities, especially the development of the "Middle Corridor", the construction of the Anaklia deep-sea port, and growing investments in the logistics sector, which are contributing to its emergence as a regional hub. The threats: The main threats are global geopolitical instability, increased security risks on navigation routes, and the impact of global crises from transit corridors

Table 7 SWOT analysis reviews Georgia's position in the context of global maritime logistics and supply chain

Strengths	Weaknesses
- Strategic geographic location at the crossroads of Europe-Asia. - Significant transit potential as the shortest route section. - The existing road and rail infrastructure (E60/E70, Baku-Tbilisi-Kars). - Operating Black Sea ports (Poti, Batumi). - Free trade agreements with the EU (DCFTA) and China.	- Infrastructural limitations and lack of coordination in the middle corridor. - Less coordination of the customs procedures with the neighbouring countries. - The need for optimization of transit costs. - Low degree of bandwidth utilization of individual port terminals. - Necessity of strengthening institutional processes.
Opportunities	**Threats**
- Global transformation of maritime logistics and supply chains creates new opportunities. - The growing importance of the "Middle Corridor/TITR" and the growth of cargo turnover. - Increasing interest in alternative, safe and politically low-risk routes. - The Anaklia deep-water port construction project and its potential. - Attracting investments in logistics infrastructure (ports, railways, hubs). - The prospect of becoming a regional transport-logistics center.	- Geopolitical and economic instability globally and in the region. - Increased safety risks on international navigation routes (eg, Red Sea). - The negative influence of global crises (pandemic, war) on logistics operations. - Competition from other transport corridors (eg IMEC, North Sea-Baltic Corridor). - Increase in transport costs due to increase in insurance rates. - Changes in the logistics models of traditional partners may affect cargo flows.

Source: Statistical data was analysed by the authors. (Batumi 2025)

5. CONCLUSIONS AND RECOMMENDATIONS

Global and regional crises of recent years, including pandemics, wars and security risks, have dramatically changed the structure of supply chains. Traditional models can no longer fully respond to modern challenges, which requires their diversification and transition to flexible strategies.

Key findings:

1. Supply chains are becoming increasingly dependent on geopolitical factors;
2. The Middle Corridor and IMEC are alternative routes to the congested and dangerous traditional routes;
3. It is possible to establish Georgia as a transit hub of the Caucasus by seeking investments in infrastructure and technology.
4. The sustainability of supply chains should be based on multi-faceted segmentation, risk management, and strategies based on regional cooperation.

Recommendations:

For Georgia:

- Deepen multilateral cooperation within the Middle Corridor;
- Accelerate the development of Anaklia Port;
- Infrastructure upgrades in Batumi and Poti ports.
- Strengthen the digitalization and harmonization of border and customs procedures with neighbouring countries.
- Increase the stability of the investment environment and encourage PPP projects in the logistics sector.
- Ensuring a stable tax and legal framework in the maritime sector.

At the regional and global policy level:

- Develop regional coordination platforms for rapid response to crises;

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APPLICATION OF IOT TECHNOLOGY FOR REAL-TIME PERFORMANCE MONITORING OF SHIPBOARD PV SYSTEMS

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Abstract

The implementation of Internet of Things (IoT) sensor technology has significantly transformed the monitoring and optimization of photovoltaic (PV) systems on ships. These advanced sensors enable real-time tracking of key parameters such as solar power generation, panel temperature, and overall system efficiency, ensuring optimal energy utilization in maritime environments. Special emphasis was placed on the integration of PV sensors for measuring the intensity of solar radiation, temperature sensors for detecting thermal fluctuations of panels, current and voltage sensors for analyzing output performance, insulation resistance sensors for preventing electrical failures. Advantages of using IoT networks and advanced analytical algorithms, data is processed in real time, enabling predictive diagnostics and early detection of potential failures. Cloud-based platforms facilitate seamless data storage and remote accessibility, enabling ship operators to make informed decisions. This paper explores the application of IoT sensors in real-time monitoring and management of renewable energy sources on ships, thus contributing to maritime sustainability. The conclusions highlight the importance of IoT technology for increasing the energy efficiency of ships, along with guidelines for future innovations in maritime affairs.

Keywords: IoT Technology; Shipboard; PV Systems; Real-Time

1. INTRODUCTION

The rapid advancement of IoT technology has significantly transformed the maritime industry by enhancing the efficiency, safety, and sustainability of vessel operations. IoT-enabled monitoring systems play a critical role in real-time performance tracking, predictive maintenance, and energy optimization of shipboard systems. Among these, the integration of IoT in PV monitoring has gained increasing attention, particularly in its application to improving energy efficiency and operational sustainability in maritime environments [1], [2], [3].

Monitoring refers to the continuous observation and analysis of key performance indicators (KPIs) within a system to ensure optimal functionality. In the maritime sector, monitoring systems are essential for tracking various operational parameters, including energy generation, fuel consumption, environmental conditions, and system health diagnostics. IoT-enabled monitoring integrates smart sensors, wireless communication networks, and cloud-based analytics to collect, transmit, and analyze real-time data, allowing for automated decision-making and improved operational efficiency [4], [5].

The implementation of IoT sensors in shipboard PV systems presents unique challenges, as these sensors must be designed to withstand harsh maritime conditions such as corrosion, high humidity, and extreme temperatures. The selection of robust materials, hermetically sealed enclosures, and advanced data communication protocols ensures the longevity and reliability of IoT sensors in these environments [6], [7]. Technologically, IoT sensors deployed in maritime PV systems encompass temperature sensors, pressure sensors, vibration sensors, and leakage detection sensors. These devices collect essential data that is transmitted wirelessly through maritime-optimized communication protocols, enabling real-time analysis and proactive system maintenance [2], [3].

IoT-based PV monitoring systems facilitate predictive maintenance by identifying potential failures before they occur, thereby reducing downtime and enhancing system reliability. The integration of machine learning algorithms allows for predictive diagnostics, ensuring optimal energy distribution and performance. Additionally, cloud-based platforms enable seamless data storage and remote accessibility, allowing ship operators to make informed decisions regarding energy utilization and system performance [8], [9].

This paper aims to show the application of IoT sensors in real-time monitoring and management of renewable energy sources on ships, with a particular focus on PV systems. It highlights the benefits of implementing IoT technology in various maritime applications, including energy efficiency optimization, operational cost reduction, and predictive maintenance strategies. The integration of IoT-based analytics with renewable energy systems enables real-time data-driven decisions that significantly enhance vessel performance [10], [11], [12], [13], [14]. One particularly relevant application is coastal maritime transport in Boka Bay (BB) in Montenegro, where the integration of IoT-enabled PV monitoring could significantly improve the sustainability of coastal navigation [15].

This paper aims to synthesize recent developments and illustrate practical applications of IoT-enabled PV monitoring in maritime environments. The paper consists of five sections. The first section introduces the importance of IoT technology in maritime PV monitoring and outlines the key objectives of the paper. The second section discusses the fundamental characteristics of IoT sensors applied in the maritime industry, including their design and operational challenges. The third section presents the technological framework for IoT-based PV monitoring, focusing on sensor integration, data transmission, and real-time analytics. The fourth section explores practical applications through case studies of IoT-enabled PV monitoring in maritime operations. The fifth and final section provides a conclusion, summarizing the key findings and outlining future research directions.

2. LEVERAGING IOT FOR SMART AND EFFICIENT SHIPBOARD OPERATIONS

The rapid advancement of IoT technology is transforming the maritime industry by enhancing the efficiency, safety, and sustainability of vessel operations. The primary aim of this paper is to investigate the integration of IoT systems with shipboard equipment, focusing on their role in optimizing energy management, enhancing condition-based maintenance strategies, and facilitating real-time data processing. By examining the technological framework, communication protocols, and operational benefits of IoT in maritime applications, this research seeks to highlight key areas where IoT-driven digitalization can enhance vessel performance [1].

This paper examines key aspects of IoT integration in maritime operations by reviewing selected recent studies and showcasing practical applications of IoT-based PV monitoring systems on ships. It explores the technological platforms that support IoT deployment on ships, particularly how sensor networks interact with centralized control systems to enhance energy efficiency, condition monitoring, and automated decision-making [2]. Another key focus is on real-time data processing and its integration with existing ship systems, assessing how IoT-driven analytics can optimize energy management systems (EMS), enable predictive diagnostics, and facilitate autonomous operational decision-making to improve fuel consumption and overall performance [4]. Finally, it assesses the impact of predictive maintenance using IoT analytics, demonstrating how real-time monitoring can enhance ship reliability by detecting early warning signs of system failures, reducing downtime, and lowering maintenance costs.

A typical IoT system architecture that represents the interaction between input sensors, processing units, and cloud-based platforms is illustrated in Figure 1. This model highlights how IoT components are structured within a maritime monitoring system, supporting the objectives outlined in this paper [2].

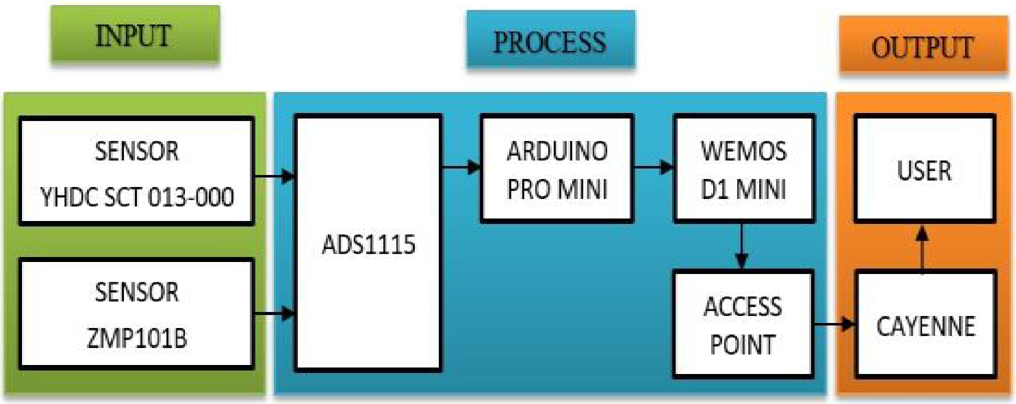

Figure 1 IoT system architecture demonstrating sensor integration, processing, and output in a shipboard environment [2]

By addressing these objectives, this research aims to provide a comprehensive overview of how IoT integration can support the transition toward smart, connected, and energy-efficient maritime operations. The findings will serve as a reference for future innovations in maritime automation, sustainability, and digital transformation, ensuring that IoT technology is effectively utilized to improve safety, operational efficiency, and environmental compliance in modern shipping [10].

3. METHODS FOR IOT-ENABLED MONITORING AND OPTIMIZATION OF SHIPBOARD PV SYSTEMS

The integration of IoT sensors into shipboard PV systems plays a critical role in real-time performance monitoring, optimization, and predictive maintenance. Due to the dynamic and harsh maritime environment, effective monitoring is essential for maintaining energy efficiency, system reliability, and long-term operational stability. To ensure efficient energy utilization and reliable operation of PV systems on ships, this paper employs a structured IoT-based monitoring approach. The methodology focuses on sensor integration, real-time data processing, and predictive analytics to optimize energy generation and minimize operational risks [6].

The following sections outline the key components of the IoT framework, including sensor selection, data acquisition strategies, communication protocols, and system optimization techniques. The research also incorporates machine learning-based predictive diagnostics to enhance preventive maintenance and improve the overall efficiency of shipboard PV systems [6].

In IoT-based PV system monitoring, accurate and continuous data collection is crucial to ensure optimal energy generation and system reliability. This is achieved through a combination of specialized sensors that track the electrical, thermal, and environmental parameters affecting PV performance. Real-time monitoring enables ship operators to detect irregularities early, preventing performance degradation and unexpected failures.

To facilitate effective sensor-driven monitoring, IoT-enabled PV systems rely on voltage and current sensors, temperature sensors and irradiance sensors. Figure 2 illustrates a typical IoT-based PV monitoring system, showcasing sensor placement, data acquisition, and communication flow for real-time performance tracking.

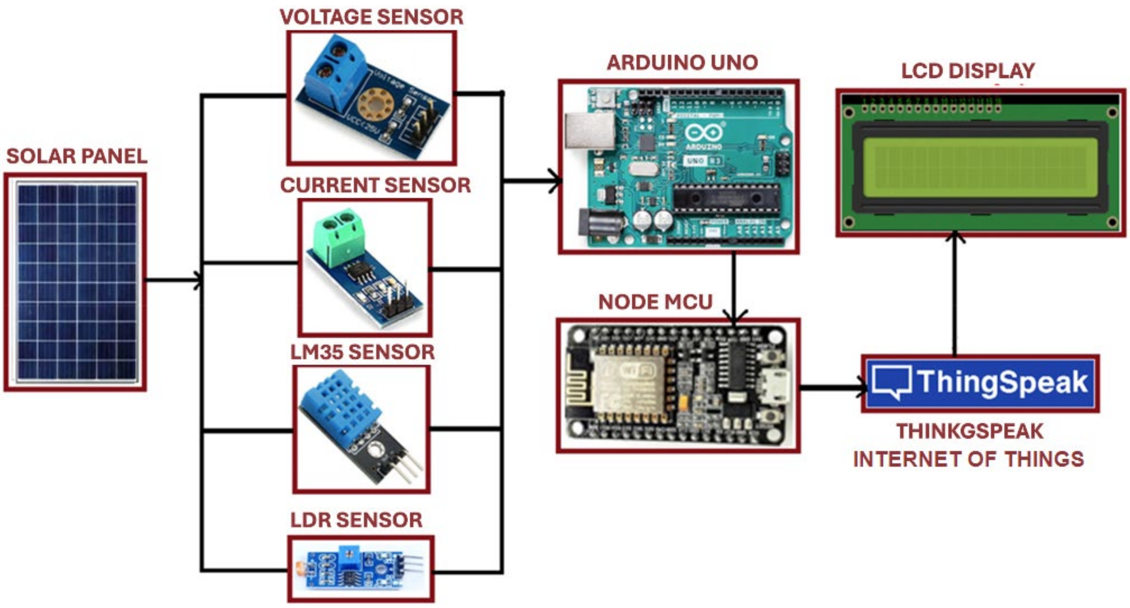

Figure 2 The proposed solar power monitoring system [6]

Implementing these sensors within an IoT framework allows for seamless data transmission to centralized systems, enabling real-time monitoring and swift decision-making to maintain optimal PV system performance [6].

3.1. Selection for Shipboard PV Monitoring

Selecting the right sensors and measurement techniques is fundamental for effective PV system monitoring. Given the harsh maritime environment, IoT sensors must be resilient to extreme weather conditions, vibrations, and corrosion while maintaining high accuracy and efficiency. This paper categorizes sensor selection into three critical groups: energy production monitoring, temperature and environmental monitoring, and fault detection with predictive maintenance.

For energy production monitoring, PV sensors measure the intensity of solar radiation reaching the panels, allowing for the assessment of energy conversion efficiency. Additionally, power meters track voltage and current output, enabling real-time performance analysis and early detection of anomalies [2]. Temperature and environmental monitoring play a crucial role in ensuring the longevity and efficiency of shipboard PV systems. Temperature sensors continuously track panel surface temperature, preventing overheating and efficiency losses [3]. Environmental sensors further enhance system reliability by measuring humidity, salt exposure, and wind conditions, thereby mitigating corrosion-related degradation [7].

Fault detection and predictive maintenance rely on advanced IoT-enabled technologies to prevent system failures. Insulation resistance sensors detect potential electrical faults before failures occur, ensuring operational stability. Additionally, anomaly detection algorithms analyze sensor data to provide predictive diagnostics, reducing the risk of unexpected power loss [9]. Through the integration of these sensor technologies, IoT-based monitoring systems enhance the efficiency, reliability, and resilience of shipboard PV systems, optimizing their long-term performance in challenging maritime environments.

3.2. Data Acquisition and Processing

The ability to collect, transmit, and analyze large amounts of data in real time is a fundamental advantage of IoT-based PV monitoring. This section details the data acquisition process, emphasizing the role of wireless communication networks, edge computing, and cloud-based analytics in optimizing PV system performance. The data processing framework is structured into three key phases: data transmission from sensors to the cloud, on-board processing using edge computing, and cloud-based monitoring and analytics.

In the sensor-to-cloud data transmission phase, sensor readings – including voltage, current, temperature, and irradiation – are transmitted via LoRaWAN, Zigbee, or satellite networks, depending on connectivity availability. A gateway device facilitates secure and low-latency communication between sensors and shipboard servers, ensuring reliable data transfer [1]. To optimize performance and reduce data transmission load, edge computing for on-board processing is employed. Critical real-time calculations, such as efficiency assessments and overheating alerts, are performed directly on the ship's local edge computing unit. Pre-filtered data is then sent to a centralized cloud for long-term storage and further analytics [4].

Finally, cloud-based monitoring and analytics leverage machine learning-based predictive models to detect performance trends and identify early signs of system degradation. A user-friendly interface provides real-time dashboards for ship operators, enabling them to monitor power output, efficiency losses, and fault notifications, thereby enhancing system reliability and operational efficiency [5]. Through this multi-layered data acquisition and processing framework, IoT-driven PV monitoring ensures optimal performance, proactive fault detection, and enhanced decision-making in maritime renewable energy systems.

3.3. System Optimization and Fault Prevention

To ensure the long-term sustainability of shipboard PV systems, IoT-based performance optimization strategies are implemented, enhancing energy efficiency, reducing maintenance costs, and extending system lifespan. This section covers three key optimization approaches: automated performance optimization, preventive maintenance scheduling, and environmental adaptation.

Automated performance optimization involves real-time adjustments to panel positioning (if applicable) and load-balancing strategies to maximize solar energy utilization. Additionally, integration with the ship's energy management system (EMS) enables intelligent power distribution, ensuring efficient energy flow across onboard systems [2]. Preventive maintenance scheduling relies on AI-based analysis to detect abnormal performance patterns, allowing for proactive maintenance before system failures occur. Operators receive automated alerts for essential tasks such as panel cleaning, wiring checks, and insulation resistance testing, minimizing efficiency losses and preventing unexpected breakdowns [8], [9].

Lastly, environmental adaptation enhances system resilience by correlating sensor data with meteorological conditions, enabling dynamic adjustments to operational parameters based on environmental fluctuations. Through these integrated optimization techniques, IoT-driven monitoring ensures reliable, efficient, and adaptive performance for shipboard PV systems in challenging maritime environments.

4. APPLICATIONS OF IOT-ENABLED PV MONITORING SYSTEMS

The implementation of IoT-based monitoring systems in shipboard PV systems has led to enhanced operational efficiency, predictive maintenance, and energy optimization. The following cases present real-world implementations of IoT for smart energy management in maritime operations.

The three selected cases were chosen based on their prominence in the literature, the availability of publicly accessible technical data, and their diverse operational contexts (oceanic, urban, and commercial shipping). These examples are not intended to be exhaustive but serve to illustrate different applications of IoT-enabled PV monitoring across various vessel types and operational scenarios.

4.1. Case 1: IoT-Enabled PV Monitoring on the Tûranor PlanetSolar

Tûranor PlanetSolar (Figure 3), the world's largest fully solar-powered vessel, features 537 m^2 of PV panels and completed a global circumnavigation in 2012 using only solar energy. This ship demonstrates the potential of IoT-integrated solar technology for long-range maritime travel [13].

The implementation of IoT-powered PV monitoring, machine learning-based predictive analytics, and cloud-based dashboards in Tûranor PlanetSolar enabled real-time energy tracking, optimization of energy efficiency under varying oceanic conditions. It also enables remote system monitoring, resulting in a 100% solar-powered circumnavigation, reduced power wastage, and a demonstration of IoT's role in integrating renewable energy into maritime operations.

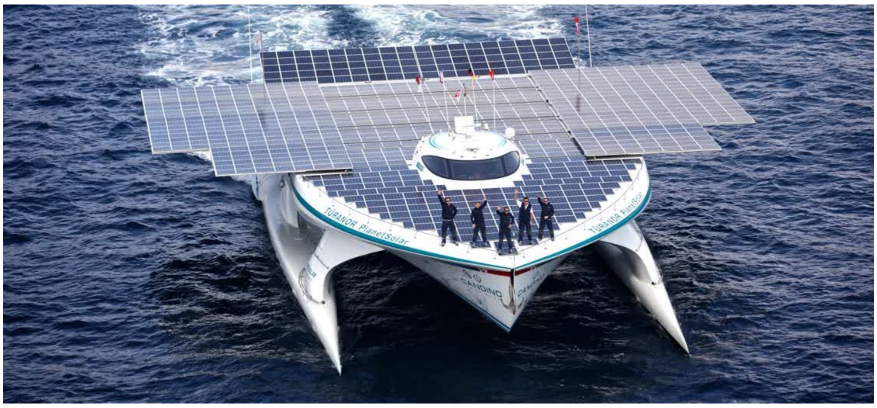

Figure 3 The first solar-powered ship to circumnavigate the globe [13]

4.2. Case 2: Aditya – Fully Solar-Powered Passenger Ferry

Aditya (Figure 4), a solar-powered passenger ferry operating in India, transports up to 75 passengers per trip over a 2.8 km route. It runs exclusively on solar energy, eliminating the need for fossil fuels and reducing urban water transport emissions [12].

The ferry is equipped with a 20 kW PV system that powers an electric motor, ensuring zero emissions and significantly lowering operational costs. An IoT-integrated real-time performance tracking system monitors energy production and distribution, detecting fluctuations and optimizing power usage. Additionally, remote diagnostics and predictive maintenance strategies prevent downtime and enhance battery performance. As a result, Aditya operates with zero emissions, offering an eco-friendly alternative to diesel-powered ferries, while achieving a 50% reduction in operational costs by replacing fuel expenses with solar energy. Furthermore, its scalable design demonstrates the feasibility of solar-powered ferries for wider urban water transport networks, paving the way for sustainable maritime solutions.

Figure 4 Aditya – The solar ferry revolutionizing urban water transport [12]

4.3. Case 3: Nichioh Maru – A Hybrid Cargo Ship with Solar Integration

Nichioh Maru (Figure 5) is a cargo vessel equipped with 281 solar panels, capable of reducing fuel consumption by 1400 tons annually and cutting CO_2 emissions by 4200 tons per year. This ship exemplifies how solar energy and IoT-based performance tracking can optimize commercial shipping operations [14].

Through real-time PV monitoring, IoT technology enables optimal positioning of solar panels to maximize solar energy absorption, while AI-driven energy analytics predict fuel savings and efficiency improvements by dynamically adapting power supply to operational conditions. Additionally, IoT-based fleet monitoring provides ship operators with remote access to energy efficiency and performance trends, facilitating data-driven decision-making. As a result, Nichioh Maru has achieved a 40% reduction in fuel consumption, demonstrating the economic benefits of IoT-integrated solar energy. Furthermore, by lowering operational costs through reduced reliance on conventional marine fuels, it has set a precedent for future commercial vessels seeking to integrate solar power and IoT-based energy management solutions.

Figure 5 Nichioh Maru – A cargo ship optimized with IoT-powered solar energy [14]

5. CONCLUSION

The integration of IoT technology in shipboard PV systems has demonstrated significant improvements in energy management, predictive maintenance, and operational efficiency in maritime environments. This paper has shown the role of IoT-enabled monitoring systems in optimizing renewable energy utilization on ships, ensuring real-time performance tracking, and reducing system failures through predictive diagnostics.

The findings highlight that IoT-driven monitoring enhances the sustainability of maritime operations by providing continuous insights into system performance, allowing ship operators to make data-driven decisions that improve energy efficiency and reduce maintenance costs. The integration of cloud-based platforms and AI-driven analytics has proven essential in processing real-time data, enabling proactive fault detection and extending the lifespan of PV systems.

The paper provides a structured synthesis of recent research combined with real-world examples that highlight the practical relevance and feasibility of IoT-based PV monitoring systems in the maritime environment. Described cases in this paper demonstrate the practical benefits of IoT-enabled PV monitoring in different maritime applications. These cases confirm that real-time data processing and IoT-enabled decision-making contribute to reduced energy waste, lower operational expenses, and increased adoption of renewable energy solutions in the shipping industry. Given the region's reliance on maritime transport for both commercial and passenger ferry services, real-time monitoring and predictive analytics could optimize energy use, improve vessel efficiency and reduce greenhouse gas emissions, especially in environmentally sensitive areas such as BB.

Despite these advancements, several challenges remain, such as the need for improved connectivity in remote maritime locations, cybersecurity risks, and the durability of IoT sensors in extreme environmental conditions. Future research should focus on developing more robust IoT architectures, enhancing machine learning models for anomaly detection to improve energy management and system reliability in maritime environments. Additionally, further investigations will examine the development of an integrated IoT platform for real-time monitoring and performance analysis of shipboard PV systems, utilizing advanced machine learning algorithms and neural networks, with a particular focus on its application in coastal maritime transport in BB.

Application of IoT-enabled PV monitoring represents a transformative approach to maritime energy management, ensuring optimized system performance and enhanced sustainability. As IoT technology continues to evolve, its application in shipboard renewable energy systems will be instrumental in driving the maritime industry toward a more resilient, autonomous, and environmentally sustainable future.

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A SMART SHIP COLLISION AVOIDANCE FRAMEWORK USING AI

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Abstract

The maritime industry faces significant obstacles to ensure safe navigation. The main aim of this project is to developed an advanced AI based ship recognition system to preclude collision in dangerous situations. The technology is packed in strategic locations close to the ship and offers real time detection of neighbouring vessels. AI algorithms help in analysing data from various sources, such as cameras and other sensors, so that potential collision hazards could easily be detected. Once it is detected, the alert notification passes through the ship's communications systems hence allowing them to make their first decision on time. In this study, the model is implemented is artificial intelligence-based deep learning model You Only Look Once, version 8 (YOLOv8). The model's object detection accuracy is 99.06% for real-time collision avoidance. The main aim of this research is to improve marine safety by elevating situational awareness and providing early warnings to stop collision avoidance at sea. The device uses powerful artificial intelligence and deep learning algorithms to automatically locate neighbouring vessels, even in difficult weather conditions like limited visibility rough at the seas. By combining data from several sensors, the system can precisely estimate the proximity and movement of nearby vessels. The detection system is strategically deployed at critical spots aboard the vessel to provide complete coverage of probable collision areas. The system immediately alerts the bridge duty officers through the ship's bridge or other integrated communication systems.

Keywords: real-time detection, collision risk evaluation, AI, deep learning, and digital alerts

1. INTRODUCTION

The maritime field faces various issues to assure safe navigation, with collisions being an essential concern that can have catastrophic effects. This initiative looks forward on establishing of an advanced AI-based ship detection system that will mitigate the hazards of fatalities at sea.[1] The device is installed at key spots of the ship, that allows quick tracking of surrounding vessels. It takes help of modern and innovative cutting-edge artificial intelligence algorithms to examine data gathered from various sensors and meticulously forecast collision menaces with high probability.[2]. Once identified, the technology informs pilots via the bridge of the vessel or any types or source of integrated communication systems, that allows quick and accurate decision-making. This technique looks forward in improving and enhancing vessel security by elevating contextual awareness and supplying early notifications.[7]. This paper aims to focus on how artificial intelligence-based ship collision detecting system is designed to improve collision avoidance at sea. Advanced artificial intelligence algorithms are used by the machines to automatically detect the surrounding vessels, despite of challenging climates such as fog or low visibility. By integrating data from several sensors, the system can precisely identify the distance and velocity of surrounding vessels. The ship detection system is proactively set up at key locations on the vessel, assuring full coverage of potential collision zones. Upon detecting a nearby ship, the system immediately alerts the bridge duty officers through the ship's bridge or other integrated communication systems, enabling them to take prompt and appropriate action.[4] AI based approach to collision avoidance not only enhances the safety of individual vessels but also contributes to overall maritime safety. Our primary aim is to develop a real-time ship detection system using AI YOLOv8 as the main goal of towards the collision risk assessment. While this paper focuses on vessel detection and classification, the system is designed to support future integration of collision prediction and COLREGS-based decision-making, The Figure 1 represents the overall flow of the proposed model.

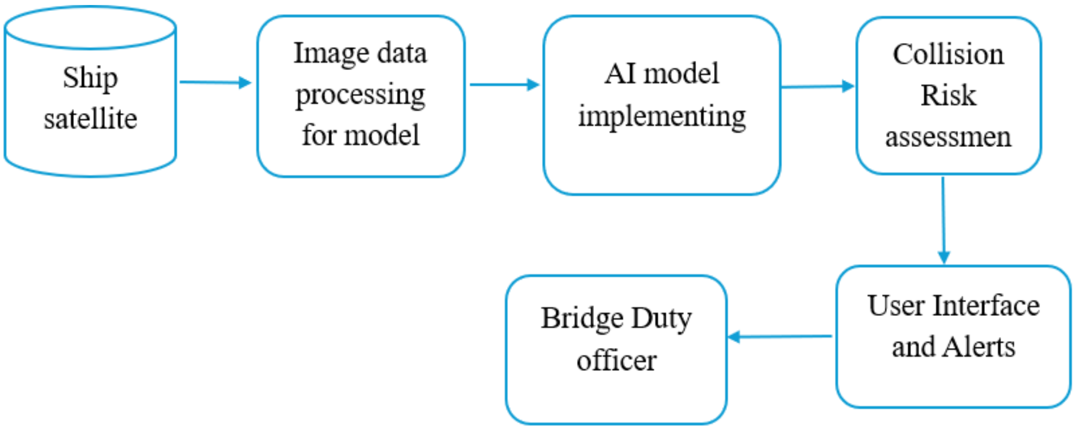

Figure 1 Workflow model for the collision avoidance system for ships using AI

2. METHODOLOGY

In this study, YOLOv8n is integrated into a real-time Artificial intelligence(AI)based ship detection and collision avoidance system to enhance maritime safety. A custom dataset was created using high-resolution satellite imagery featuring annotated vessels captured under various environmental conditions, including low visibility and rough seas. Table 1 describes the detailed parameters of the YOLOv8 model used for training.

Table 1 YOLOv8 Model Parameters used for Training

Parameters used	Description
Model Variant	YOLOv8n (nano)
Input Image Size	640 × 640 pixels
Optimizer	SGD
Learning Rate	0.01
Number of Epochs	20
Batch Size	16
Evaluation Metric	mean Average Precision (mAP)
Accuracy Achieved	99.06%

The trained YOLOv8 model was integrated into the ship's onboard Artificial intelligence (AI) system to process sensor and video inputs in real time, detect nearby vessels, and provide data to a collision risk assessment module. When a potential threat is identified, the system immediately alerts bridge officers through the navigation interface or communication channels, enabling timely and informed decision-making to enhance maritime safety. The development of the AI-based ship detection system follows a structured approach, integrating advanced technologies and systematic testing which is represented in Figure 2.

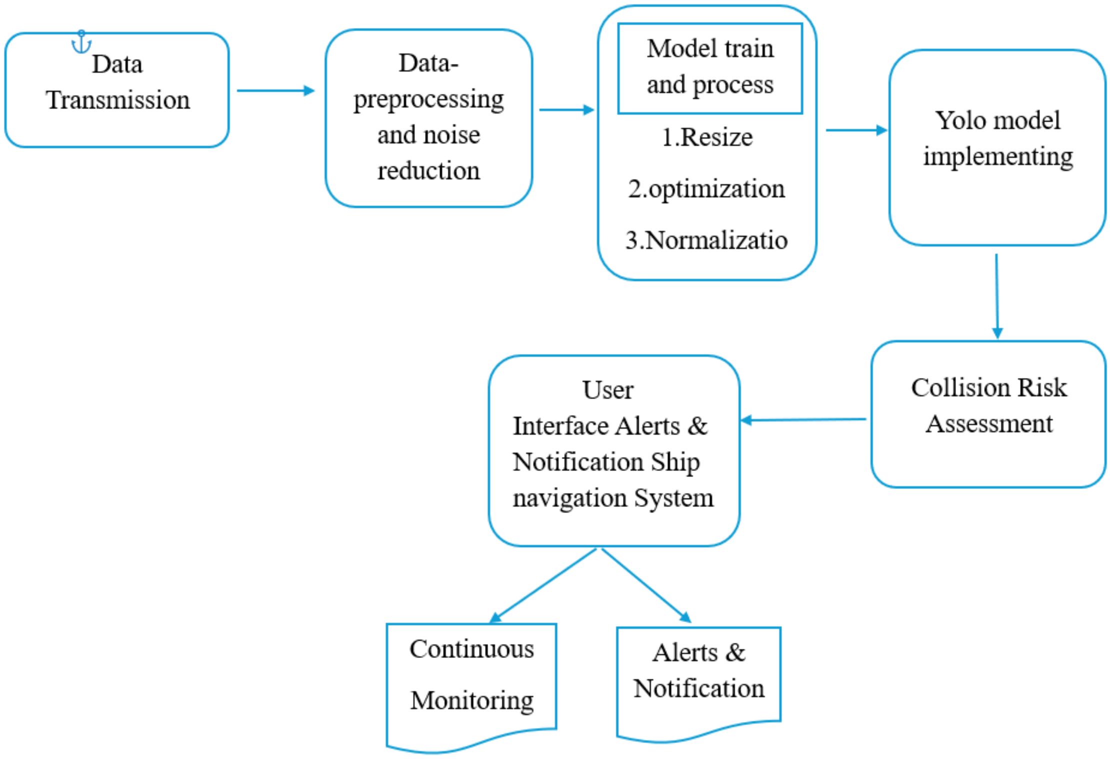

Figure 2 Architecture model and dataflow diagram for the collision avoidance system for ships using AI

2.1. System Design and Architecture

The first step in developing the Artificial intelligence-based ship collision avoidance framework is to establish a robust and scalable system architecture. This design combines numerous sensor modalities, including high-resolution optical cameras, to provide full situational awareness across a wide range of marine situations. The modular architecture enables adjustable sensor integration based on vessel type, operating requirements, and climatic conditions. The design enables smooth data fusion from several sources, allowing for real-time perception of nearby ship activity and possible navigational dangers. It was designed to be adaptable, allowing for future upgrades or the inclusion of emerging sensor technologies without requiring a significant structural redesign.

2.2. Data Collection and Preprocessing

To ensure high model accuracy, reliability, and flexibility in real-world maritime environments, a large dataset of ship interactions was collected under a variety of operational and environmental conditions. Data were collected from both publicly available marine databases and commercial video footage captured by ship collision detection systems. The publicly available datasets offered broad visual coverage of numerous vessel types from several viewpoints, but the individual recordings provided realistic, close-range footage captured under dynamic sea conditions. The dataset was marked with bounding boxes and labelled with vessel classifications such as ships, boats, cargo ships, tankers, fishing boats, bulk carriers, and passenger ships. It also allowed the model to differentiate between different types of marine boats, vessels, which improved its capacity to respond effectively in mixed traffic scenarios. After collecting the dataset preparation pipeline was used to prepare it for training. Filtering was used to minimize picture noise, especially in foggy and wet settings, while histogram equalization techniques improved contrast and visibility in low-light scenarios. All data obtained video frames were scaled and normalized to ensure a uniform input resolution for the You Only Look Once (YOLOv8) model. Annotations were structured using the You Only Look Once (YOLO) framework, which ensures precise spatial representation of objects during the learning process. Data collection and preprocessing played a vital role in maximizing the performance and reliability of the collision detection system, providing a strong foundation for subsequent training and deployment phases.

2.3. Model Selection

To obtained high-accuracy object detection and real-time operating in marine environment carefully selects this model. The Convolutional Neural Networks (CNNs) were selected because they provide the extract complex detection for the marine data. To facilitate real-time vessel recognition and classification, the You Only Look Once, version 8 (YOLOv8) model was chosen for its lightweight design and high inference capabilities. And cutting-edge object detection. Making it ideal for real-time use in navigation scenario systems. Its efficacy including frame-per-second (FPS) rates, detection level of assurance, and localization precision, showed its suitability for marine safety applications.

2.4. Model Training

The selected algorithms were developed on a dataset consisting of many high-resolution marine image datasets and recovered video frames. Each data object had been assigned valuable marine data, including vessel type, cargo, fishing, tanker size, heading, and environmental conditions. To reduce overfitting and increase model generalizability, several methods for enhancing data were employed, such as linear transformations, brightness modulation, Random blur, and artificial noise overlays. Model training improved by allowing for quick and efficient. To ensure optimal model and minimal detection errors, key parameters such as learning rate, batch size, number of epochs, and anchor box sizes were fine-tuned during training and continuously monitored using metrics such as loss convergence, mean average precision, and intersection over union scores.

2.5. Model Development

Throughout the model-building stage, CNN-based feature extractors were integrated with the You Only Look Once, version 8 (YOLOv8) detection system. This combined development allows both the complete detection of vessel qualities and quick localization in high-resolution frames. The technology was developed to recognize, monitor, and classify boats and ship in in real time scenario, allowing for predictive collision avoidance and navigation. In the process of model building several marine datasets proved to the model for reliability, implementing evaluation standards real-time detection operational deployment [5].

2.6. Device Configuration

The system implementation for real time operation in marine environment is based on a well engineered system on high resolution cameras and environmental sensors operating at the top of location in the vessel such as bridge for 360-degree safety coverage of potential hazards. These sensors relay their inputs to an on-board processing unit which is deployed in a powerful Graphics Processing Unit (GPU) used to perform AI prediction. The system is fully interfaced with the vessel's existing navigation and communications equipment, including alarm relay and bridge panel displays, enabling instant crew warning to dangers perceived. All hardware components are protected in waterproof to marine grade, ensuring long-term installation in dangerous environments.

3. RESULT

The accompanying images show the AI base vessel identification system has been able to detect and track the closest boats in a variety of marine environments. The You Only Look Once, version 8 (YOLOv8) model accurately detected ships under difficult monitoring conditions including dangerous scenario. The real-time processing capacity to measure possible collision dangers and identified immediately, providing the crew enough time to take corrective action.[6]. Also, it demonstrates the system's performance in various settings, highlighting its strength and reliability to improve marine safety. The discussion demonstrates that the integration of the current sensor framework has significantly situational awareness on board, minimizing the risk of a collision. The device reduces human watch standards and adds an extra layer of safety, recognizing vessels in real time under difficult situations.

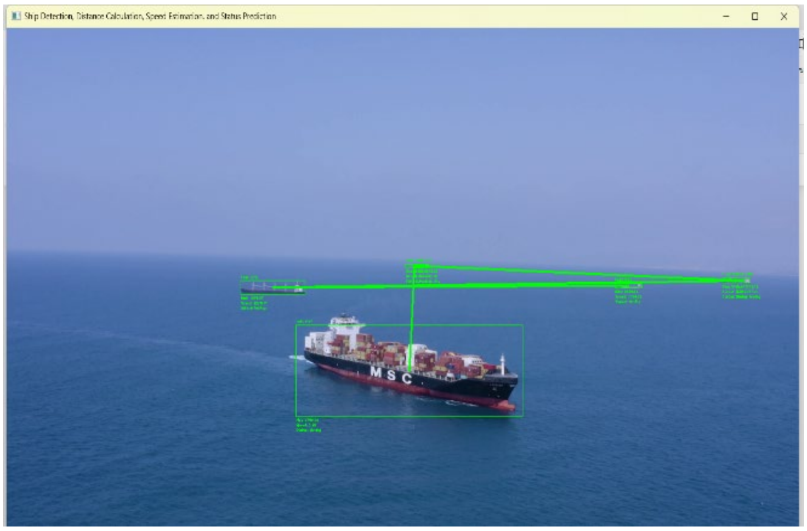

Figure 3 Show the AI-based collision avoidance for real-time ship detection

This proposed AI-based ship detection system integrates COLREGs (International Regulations for Preventing Collisions at Sea) by using YOLOv8n such as vessel position, speed, and bearing to classify encounter types and assess collision risk assessments [3]. This model provides alerts and navigational recommendations. The model was verified under varied conditions, including as fog, night, stormy seas, and high-traffic situations, using a multi-environment test dataset. Demonstrating robustness and reliability for real-time maritime collision avoidance.

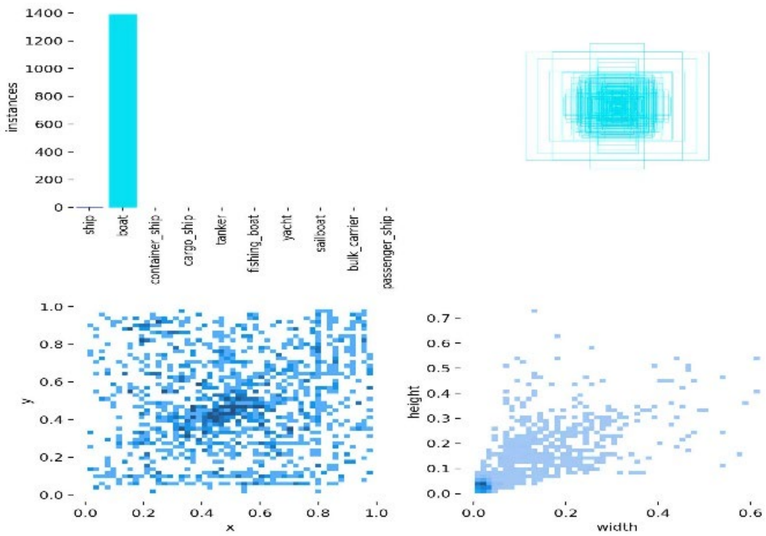

Figure 4 The image and label distribution plot for the ship satellite image

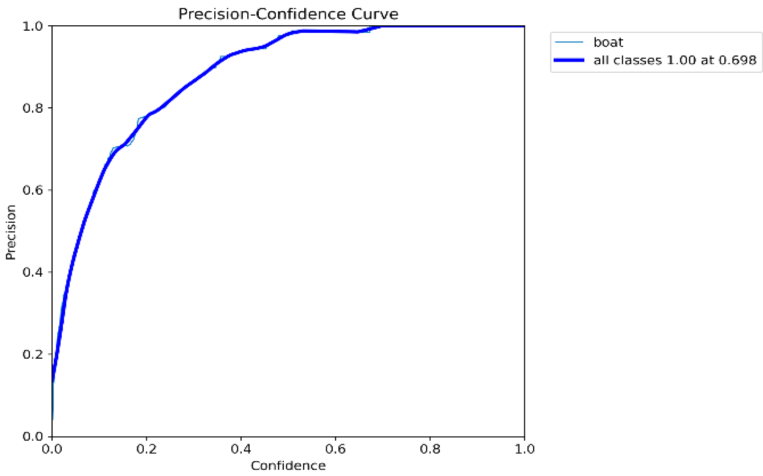

Figure 5 Representation of the accuracy plot of the model

4. DISCUSSION

This study highlights the possibilities for using AI and computer vision into marine safety systems. The suggested framework promotes safer navigation by enabling real-time ship identification and improving situational awareness, while also aligning with international standards for decision-making for bridge officers, and reduces reliance on human vigilance in complicated or high-risk circumstances. The solution also helps to achieve larger objectives in smart shipping and intelligent marine infrastructure. By seamlessly integrating with current navigation infrastructure, the system provides a viable alternative for increasing safety without requiring substantial adjustments. The wide ramifications of this work point to the rising viability of AI in autonomous and semi-autonomous marine systems will enable more efficient and safe operations.[8] However, it highlights the need for additional improvement, such as improvements in managing extreme weather conditions and complex marine traffic, as well as studies on the integration of various sensor modalities. Overall, the study found that intelligent vision systems can help define the future of marine navigation. Its deployment graphics Processing Unit (GPU) technology.

5. CONCLUSION

A major step taken towards maritime safety and resourceful navigation is the AI-based ship collision avoidance framework, that has an astounding 99.06% rate of detection that uses YOLOv8 model. This elevated level of meticulousness focuses on exact vessel identification as well as early warning notifications, that leads to minimizing or reducing the probability of marine collisions. Prevailing navigational structures, such as bridge alarm systems and radar networks when associates with the system certifies smooth functioning and elevates the capacity of crew members to make choices at the right time. Environmental conditions such as fog, rain, and nighttime visibility, reflects the system's ability to adapt to changing marine scenarios. Climatic conditions such as fog, rain, and poor visibility reveal its toughness and adaptability to changing marine environments. It facilitates to the broader area of autonomous and semi-autonomous navigation making a huge impact on industrial and commercial uses. Additionally, the hardware and software designs are flexible enough to enable scaling and modification, making it suitable for arrangement on a range of vessel types, from fishing boats to cargo ships. Modifications and alterations designs is allowed as per the flexibility of the hardware and software, that permits implementation on a varied range of vessel types, avoiding incidents. This innovation paths the way for future advances in intelligent marine systems. In years to come, the innovation might be executed with Geographic Information Systems (GIS) to improve spatial awareness and route planning. GIS provides an outline for obtaining, planning, and displaying geographical information, empowering more advanced collision risk assessments and operational decision-making.

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SAILING INTO THE GAP: EXPLORING BRANDING IN INDUSTRIAL CLUSTERS AND THE MISSING MARITIME LINK

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UDK 659.1*658.8:656.61

Abstract

Branding in industrial clusters has emerged as a crucial strategic activity to enhance collective identity, visibility, and competitiveness, particularly within business-to-business (B2B) contexts. While existing research covers branding practices to some extend across industrial ecosystems, the application and development of branding strategies within maritime clusters remain underexplored. Current study conducts a systematic literature review focusing on peer-reviewed research to map existing knowledge on branding in industrial clusters and to identify the extent to which maritime clusters have been included in this discourse. It aims to unfold under researched areas and proposes for future research on maritime cluster branding. Findings reveal that while industrial cluster branding is a well-established research field, branding within maritime clusters has received limited scholarly attention. By mapping the evolution of industrial cluster branding research and revealing the maritime cluster branding gap, this study offers a conceptual foundation for future investigations. It highlights the need for a deeper understanding of collective brand identity formation, stakeholder coordination, and promotional strategies in maritime industry clusters operating within B2B environments.

Keywords: Industrial Cluster, Branding, Maritime Cluster, B2B branding

1. INTRODUCTION

The maritime sector, composed of a diverse network of interrelated actors, increasingly benefits from industrial agglomeration which is a foundational concept that explains how geographic concentration of industries fosters economic efficiency, innovation, and competitiveness. Originally introduced by Marshall [1] through the notion of industrial districts, agglomeration emphasizes how proximity enables firms to leverage specialized labour, nearby suppliers, and localized knowledge spillovers. Porter [2] later expanded this idea into cluster theory, highlighting the role of both collaboration and competition within geographically concentrated industries in driving innovation and enhanced performance. In the maritime context, these dynamics have come forward in the form of maritime clusters, where actors such as shipping companies, ports, shipyards, maritime logistics providers, IT firms, and supporting services co-locate to exploit the advantages of proximity. Through access to skilled labor, shared infrastructure, institutional support, and innovation ecosystems, these clusters reinforce regional and national competitive advantage.

Branding plays a critical role in business-to-business (B2B) marketing by enabling firms to differentiate themselves through service quality and value, especially in markets with commoditized products [3]; [4]. This logic extends to industrial clusters, where collective branding strategies enhance competitiveness and visibility. Unlike corporate branding, cluster branding involves complex coordination among diverse public and private stakeholders to build a shared identity and promote the region [5], [6].

Recent studies emphasize how strong cluster branding supports regional competitiveness by harnessing shared image, fostering external engagement, and enhancing global recognition [7], [8].

Successful cases like Datang, Pisa, and Oulu show how branding drives economic growth, although challenges remain, especially for clusters dominated by MSMEs [9]–[12].

In B2B contexts, brand equity, customer satisfaction, loyalty, and relationship quality are key to build industrial brand equity and competitiveness [13], [14]. Branding is also influenced by sustainability concerns, design perception, and emotional engagement[15], [16]. While branding in tourism and cultural industries is well-explored, its application to industrial clusters, particularly in the maritime sector, remains limited and requires further attention [17], [18].

Given this background, this study aims to explore conceptual overlaps and divergence between industrial cluster branding within B2B perspective and maritime literature and shed light on underexplored themes and opportunities for theoretical convergence. This effort is important for further advancing the maritime cluster literature by creating coherent understanding of maritime cluster branding, policy makers, and industrial stakeholders. The rest of the paper structured as follows: Methodology for systematic literature review was given in second section; third section provided the findings of the research; discussion and potentials for further studies was pointed on in section four; and last section concludes the research.

2. METHODOLOGY

The study used a systematic literature review (SLR) approach [19], following the PRISMA protocol to ensure a transparent, replicable, and reliable review process [20]. The search was conducted in the Web of Science database, focusing on English-language articles without time limits. The review followed a structured process of identification, screening, eligibility assessment, and inclusion.

This study employed an iterative search strategy in the Web of Science database to identify relevant literature on industrial and maritime cluster branding. The identification, screening, and eligibility stages overlapped due to the complex nature of the topic. Search parameters, including research strings, language (English), and search fields (title, abstract, keywords), were defined in advance. Multiple search attempts ensured comprehensive coverage, as detailed in Table 1.

Table 1 Search Inquiry

Inquiry Group	Research String	Search Field and Output
Group 1	("industrial cluster*" OR "business cluster*" OR "regional cluster*" OR "innovation cluster*" OR "agglomeration*" OR "competitiveness*") AND ("branding*" OR "marketing*" OR "identity*" OR "reputation*" OR "promotion*" OR "positioning*" OR "differentiation*") AND ("collaboration*" OR "networking*" OR "alliances*" OR "partnerships*" OR "business networks*") AND "maritime*".	All field (N=32)
Group 2	("industrial cluster*" OR "business cluster*" OR "regional cluster*" OR "innovation cluster*" OR "agglomeration*" OR "competitiveness*") AND ("branding*" OR "marketing*" OR "identity*" OR "reputation*" OR "promotion*" OR "positioning*" OR "differentiation*") AND ("collaboration*" OR "networking*" OR "alliances*" OR "partnerships*" OR "business networks*")	All field (N=1175)>Topic (N=537)>Author Keywords (N=5)
Group 3	"brand*" AND (("industrial cluster*" OR "business cluster*" OR "regional cluster*" OR "innovation cluster*") OR "B2B*")	Topic (N=465)> Author Keywords (N=96)
Group 4	"maritime cluster*"	All fields (N=107)

Several search rounds were carried out using different groups of keywords, revealing a scarcity of publications linking industrial cluster branding and maritime cluster branding. This led to a shift in the study's focus toward a comparative exploration of both fields. As inclusion process, publications from each field were collected and analyzed separately to draw field-specific insights and build a shared conceptual understanding. In total, 96 articles on industrial cluster branding and 107 articles on maritime clusters were included for analysis.

3. FINDINGS

3.1. Industrial Cluster Branding Theme

The papers analysed through VOS viewer, focusing on intellectual structure and thematically. A keyword occurrence analysis was applied to reveal the relationship between the fields and unveil the hidden gap in the domain. The Figure 1 illustrated the network structure of the keywords in selected publications.

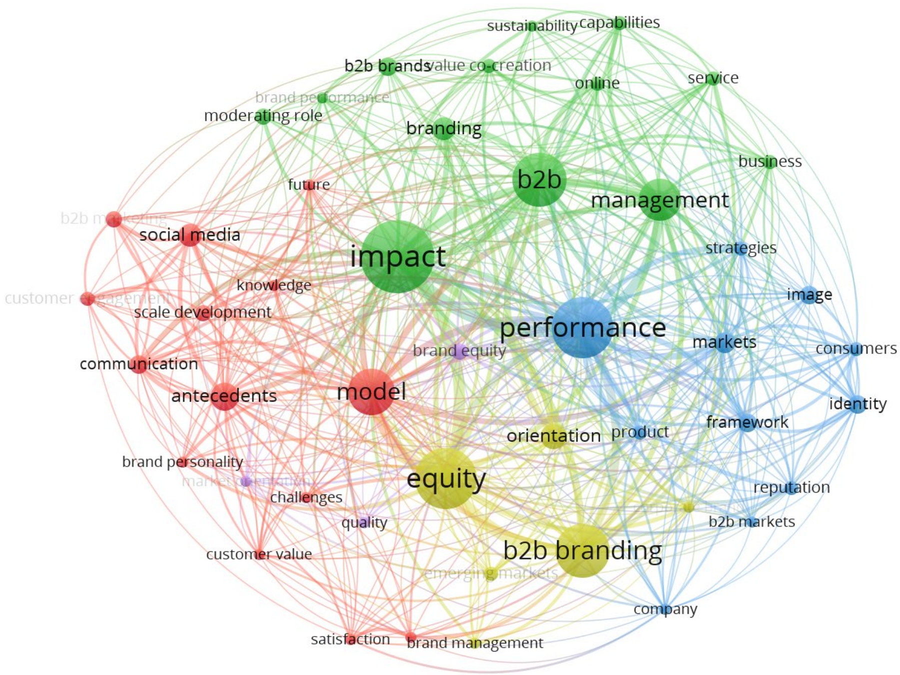

Figure 1 Keyword Co-Occurrence of selected Publications

Cluster 1 (Red, Foundations of B2B Brand Identity and Measurement) is characterized by a customer-centric perspective, focusing on the theoretical underpinnings of branding, value creation, value co-creation, customer engagement, and firms' strategies for overcoming branding challenges in complex B2B environments. The stable research trajectory observed between 2013 and 2023 suggests the continuation of established research trends rather than the emergence of new thematic directions.

Cluster 2 (Green, Strategic Branding and Managerial Capabilities in Industrial Clusters) emphasizes the role of strategic orientations, managerial and marketing capabilities, and firm innovation in shaping brand performance outcomes. The focus lies on how organizational capabilities are leveraged to achieve measurable branding success, beyond traditional notions of brand image and identity.

Cluster 3 (Blue, Performance Evaluation and Organizational Value Outcomes) integrates strategic brand positioning, organizational identity, and market engagement with performance-oriented approaches. It highlights the dual role of "performance" as both an outcome variable and a construct used to assess branding strategies, with a methodological emphasis on frameworks and strategic models.

Cluster 4 (Yellow, Brand Equity as a Strategic Asset in B2B Branding) foregrounds brand equity as a critical, measurable asset within B2B branding strategies. The prominence of terms such as corporate brand and brand management further suggests an organizational-level focus on brand governance and identity management.

Cluster 5 (Purple, Brand Value and Equity in Market-Oriented Branding) is the smallest thematic cluster, it focuses primarily on brand equity, market orientation, and quality, indicating a niche but coherent stream of research contributing to the broader discourse on market-driven branding strategies.

On the other hands the network structure can also sign the trajectory of the keywords over the years. Figure 2 illustrates the evolution of the keywords in selected publications over the years.

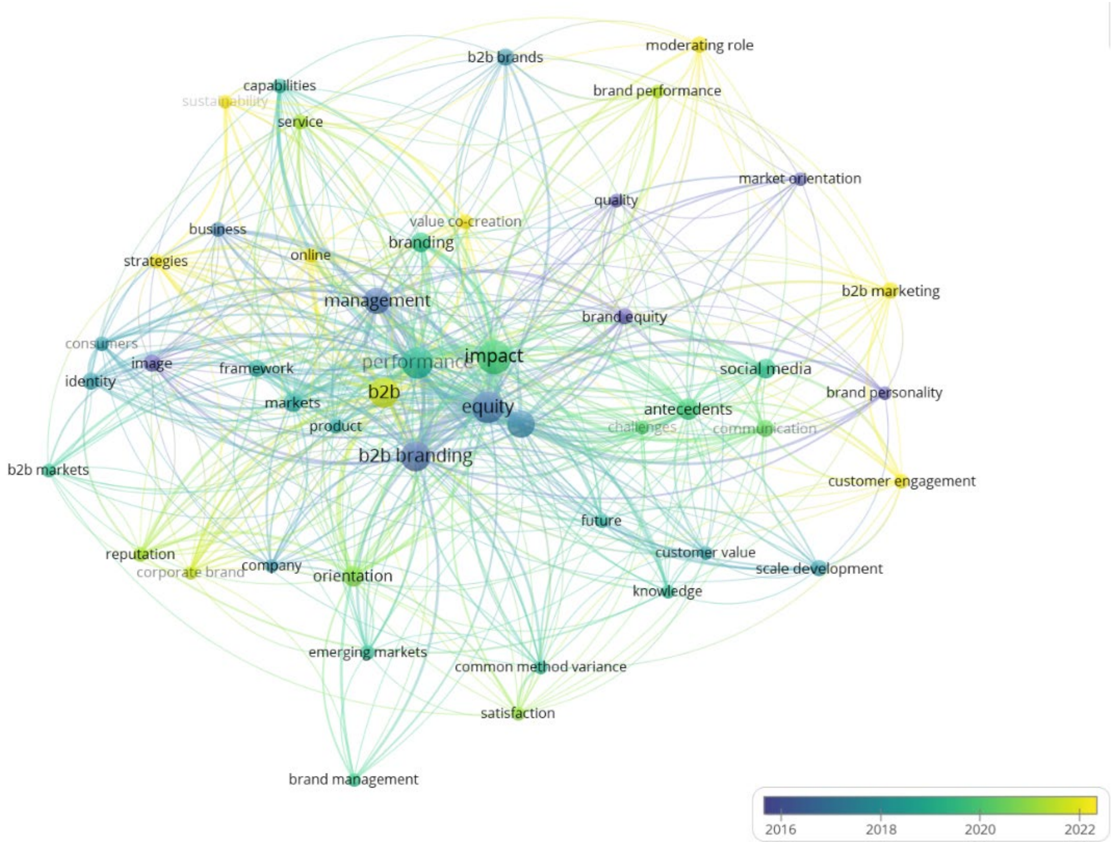

Figure 2 Research Field Evolution over the Years

The thematic landscape of inquiry shows a recent yet sustained interest in topics such as customer engagement, value co-creation, and digital integration, particularly from 2013 to 2023. Emerging themes like sustainability and digitalization have gained traction since 2021, while foundational concepts like brand equity, performance, and frameworks have remained central to both empirical and theoretical research between 2015 and 2020.

3.2. Maritime Cluster Theme

The VOS viewer analysis identified four thematic clusters in the maritime cluster literature. Cluster 1 (Strategic-Institutional Core) highlights innovation, policy, cooperation, and performance, emphasizing the role of innovation governance and the strategic impacts of collaboration among maritime actors. Cluster 2 (Growing and Competition) focuses on organizational and strategic mechanisms driving cluster growth, with strategy, management, and competitiveness as key themes. Cluster 3 (Maritime Cluster Evolution) captures a more conceptual and structural understanding, with strong emphasis on systems, models, and theoretical frameworks that explain the development and transformation of maritime and port clusters. Together, these clusters reflect a blend of strategic, institutional, and theoretical approaches shaping the field.

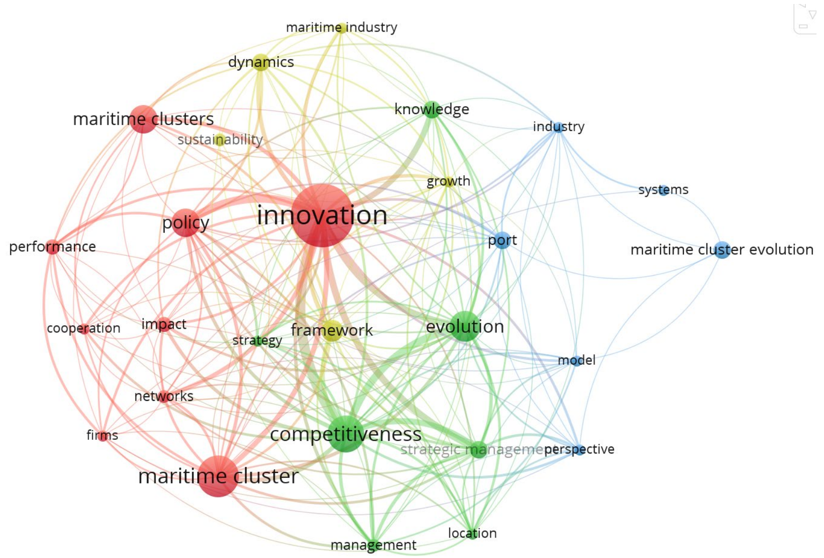

Figure 3 Keyword Co-Occurrence of Maritime Cluster Literature

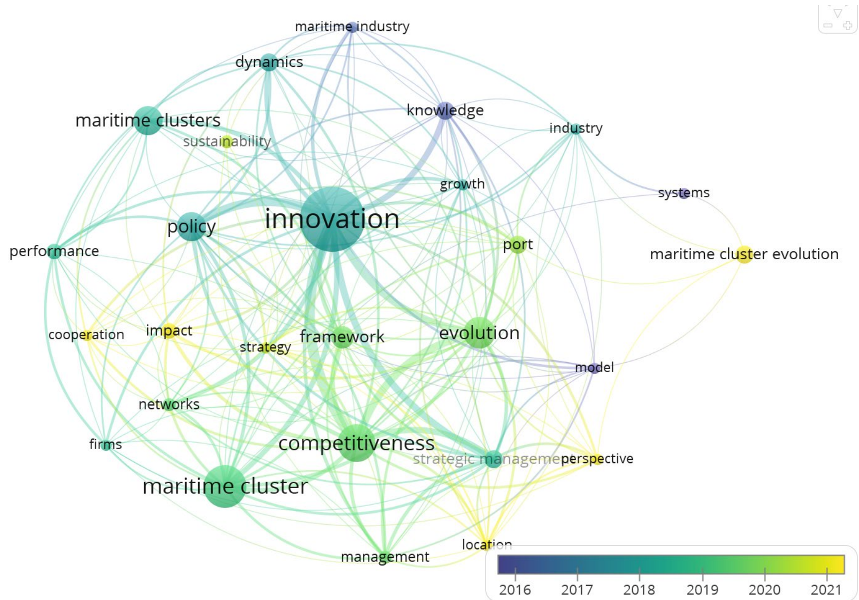

Figure 4 Keywords Distribution in Maritime Cluster Literature

Cluster 4 (Growth Perspective) focused on developmental, conceptual, and sustainability dimensions, centering around themes such as framework, dynamics, growth, and sustainability. Research within this cluster highlighted an evolving trajectory toward understanding structural changes and developmental dynamics in the maritime industry, with a growing emphasis on sustainability. The temporal distribution of keywords from 2014 to 2022 revealed both the persistence of foundational concepts and the emergence of new themes.

Clusters 1 and 2 demonstrated the most recent average publication years, indicating ongoing interest in innovation, cooperation, strategy, and management. Notably, keywords like "cooperation" and "maritime cluster evolution" emerged in 2022, while older threads such as "systems" and "model" remained foundational but reflected less recent publishing activity (See Figure 4).

4. DISCUSSION AND POTENTIALS FOR FUTURE STUDIES

The concept of industrial cluster branding and regional competitiveness have received increasing scholarly attention. Studies show how clusters leverage collective identity and image for recognition and competitive advantage (e.g.[7], [8], [21]), boosting external stakeholder engagement. Global competitiveness drives cluster success, illustrated by Datang Hosiery and high-tech regions like Pisa and Oulu [9], [10], though small and medium enterprises (MSMEs) face branding challenges [11], [12]. On the other hand in B2B contexts, research stresses the roles of customer satisfaction, loyalty, and relationship quality in building industrial brand equity (e.g. [13], [22], [23]. Seller-buyer interactions foster long-term brand engagement (e.g., [24], [25]). Green branding and corporate social responsibility (CSR) highlight the importance of sustainable brand personalities [15], [26], [27], while brand design studies show the influence of logos and design architectures [16], [28]. Given these insights, it becomes clear that the branding of industrial clusters does not occur in isolation. Instead, it often intersects with broader regional narratives and identity building efforts. This convergence invites closer examination of place branding. In the current literature, place branding was pointed out how cultural assets and social media enhance regional influence [29], [30]. However, the role of umbrella organizations in shaping industrial branding strategies, especially in B2B markets, remains underexplored. Direct studies on industrial cluster branding reveal a diverse field. Aligning value propositions with customer needs is central [31]. Tourism and destination branding contribute to regional competitiveness but are less applied to industrial clusters [32]. Cultural branding and urban development strategies support cluster promotion [18].

As one of the branch of industrial clusters, maritime clusters are conceptualized as industrial complexes, innovation-driven agglomerations, or community networks [33], with industries like shipbuilding and maritime logistics collaborating for competitiveness [32]; [33]; [36]; [37]–[39]. Cluster structures and governance differ based on regional factors[33], [40], [41]. This topics in industrial branding and competitiveness naturally extends to the maritime domain.

In maritime domain, competitiveness remains a major theme, assessed through benchmarking and strategic differentiation[42], [43], with studies also evaluating the economic potential of emerging regions [44], [45]. Similar concern regarding the governance challenges in industrial branding, governance challenges persist [46].

Maritime clusters contribute significantly to regional development [47], [48], a contribution that is further shaped by infrastructure developments and industrial relocations, as illustrated in the Panama Canal expansion and port-originated clusters like Shanghai and Dalian [40], [49], [50], [51]. These shifts have also prompted research into global cluster hierarchies and ongoing transformations [52], [53], [54].

Looking ahead, innovation, sustainability, and knowledge-sharing processes are critical for cluster competitiveness [55], [56]. New frameworks stressed open innovation and co-creation [57], pushing for rethinking traditional cluster models to address governance, sustainability, and strategic positioning [58].

Given the topics and themes framed in both domains, the future studies in both fields of research are multifaceted, and common framework can be built regarding the relatively scarcity of the papers in intersected field. In industrial branding context, branding can be considered as a subject for examine the role of managerial/organizational practices in building successful industrial branding within B2B context. Regarding the umbrella organization practices, the role of those in building brand could be a subject of further studies. Besides, industrial cluster branding dynamics may show difference from the traditional corporate branding in terms of customer relationship building. The reflections of traditional corporate branding on B2B branding practices specific to industrial cluster can be considered as a subject.

The research trajectory of industrial cluster branding in B2B context studies showed that the most recent themes in the stream are virtual touchpoints like social media, and online, sustainability, customer engagement, and value co-creation point on digital transformation. These emergent themes, yet still have rooms for further studies, examining the role of digital platforms building/shaping the brand identity and strategy, analysing the dynamics and strategies sustainability-driven industrial cluster brand building.

One possible way for further studies is to form cluster identity to be considered as a subject of extending the branding dynamics and brand models to cluster level and the effect of multi-actor environment on building collective brand identities, and the role of non-firm actors in decentralized brand ownership forging on brand equity.

On the other hand, branding-focused maritime cluster literature is still in its infancy, thereby it offers a valuable opportunity to connect it with the broader field of industrial cluster branding. Driven by rising influence of contemporary imperatives, the research context of branding in maritime industrial clusters may be shaped around innovation sustainability, policy development, competitiveness, growth and identity formation. These themes can be extended to explore the interplay between regional innovation system and branding practices, collaboration mechanism that shape the unified cluster identities, the role of identity and sustainability on performance and competitiveness. Further, exploring dynamic capabilities required for brand transformation and comparing maritime branding strategies with those of other industrial clusters can help uncover both shared and sector-specific challenges. Together, these inquiries offer a structured approach to understanding the complexities of maritime cluster branding within the broader industrial branding discourse.

5. CONCLUSION

This study explored the current advancement industrial cluster branding literature and reflection of the topic in maritime domain through systematic literature review. While industrial cluster branding is relatively developed field focusing on theoretical bases of B2B brand identity; strategic branding and capabilities; performance and organizational value outcomes, brand equity as a strategic asset; brand value and equity in market-oriented branding, maritime cluster, instead, remained more focused on institutional and competitiveness aspects, with minimal attention to branding.

The analysis revealed a clear gap between both domains. Regarding the research inquiry made with the set criteria, branding is a missing spot in maritime cluster context despite its potential to enhance collective identity, stakeholder engagement and strategic visibility. Such a spot offers avenues for integrating branding strategies into maritime cluster development. Future research may bridge these fields that enrich both theory and practice, offering new pathways to strengthen maritime cluster positioning in global networks.

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DECARBONIZATION OF ESTONIAN FERRY LINES – CHALLENGES AND OPPORTUNITIES

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Abstract

Decarbonization in the shipping industry plays a central role in global research and innovation activities. Ways to achieve zero-emission shipping include energy efficiency improvements, operational changes, the use of non-fossil fuels, retrofit and redesign of ships. Although the environmental regulations of the European Commission and the International Maritime Organization (IMO) apply only to ships above 5000 GT, the local industry representatives and authorities in many European counties also target greenhouse gas (GHG) emissions reduction from a wider shipping sector, including smaller ships and island ferries. To achieve the GHG emissions reductions, low-carbon fuels such as biodiesel, hydrogen, and its derivatives have been proposed for ferries along with direct electrification. From the design and operation viewpoint, these alternatives involve higher investment risk, including (a) capital-intensive infrastructure requirements, (b) powertrain implementation and onboard storage sizing, and (c) fuel availability and price volatility. This study focuses on an Estonian ferry line, which serves as the primary means of transportation for connecting the mainland. Consequently, it plays a critical role in facilitating the mobility of cargo and passengers to and from the islands. We analyse possible future energy system development paths to evaluate potential alternative fuels, based on existing ferries and local port infrastructure. Subsequently, we develop and apply an energy-transport optimization model to analyse alternative fuel investments from a techno-economic-environmental viewpoint. Finally, we present a preliminary comparative analysis of GHG emissions reductions and operating costs from the perspective of energy consumption, supporting the industry's decision makers in evaluating the future competitiveness of the shipping lines.

Keywords: decarbonization, shipping, alternative fuels, electrification

1. INTRODUCTION

The European Commission has adopted the Fit for 55 initiative to align the EU's policies on climate, energy, transport, and taxation with its target of reducing net-zero GHG emissions by at least 55% by 2030 [1]. This aligns with the European Green Deal, which aims to achieve net-zero emissions by 2050. Estonia's National

Energy and Climate Plan (NECP 2030) sets similar goals, targeting a 70% reduction in GHG emissions by 2030 and 80% by 2050, compared to 1990 levels [2].

Currently, IMO and EU GHG regulations focus on ships larger than 5,000 GT, with some rules applying to those over 400 GT. However, FuelEU Maritime [3], coming into effect on January 1, 2025, introduces exemptions for certain vessel categories, including passenger ships operating between islands with fewer than 200,000 inhabitants. Additionally, various vessel types- such as fishing boats, tugs, waterbuses, and pilot boats- are currently excluded from EU decarbonization regulations. Despite being smaller in size, these ships contribute to an estimated 15–20% of total maritime GHG emissions [4], highlighting a substantial regulatory gap.

Efforts are made to incentivize low-carbon fuels and power solutions with GHG intensity limits on energy used on board the ships. Nevertheless, the European Maritime Transport Environmental Report 2025 [5] reveals that the use of alternative fuels and sources of power has increased, despite being still marginal.

Estonia, located in northeastern Europe, has a population of approximately 1.3 million [6] and a coastline of about 3 800 km, nearly six times longer than its mainland border. It includes around 2 200 islands, many of which, especially in western Estonia, are historically and presently dependent on maritime transport.

Saare County, which includes Saaremaa (the largest island in the Baltic Sea) and Muhu (the third largest island in Estonia), has a low population density of 10.9 inhabitants per square kilometer [6]. These islands are primarily accessed by ferry services, with only limited support from aviation. Most passengers and cargo rely on a combination of sea and road transport.

This study focuses on an Estonian ferry line that operates between the mainland (port of Virtsu) and Muhu island (port of Kuivastu). Muhu island is connected to Saaremaa Island with a causeway, making the ferry connection the primary link to the mainland for the population of about 34 000 people [7]. Currently the ferry line has two double-ended ferries: one with conventional diesel engine and the other one with diesel-electric hybrid engine. In this study, we evaluate and assess the following research questions: (1) What is the energy demand for the ferry line under varying weather conditions? (2) Can this line be operated by fully electric plug-in hybrid ferries? (3) What are the GHG emission reductions and fuel operating cost savings if electric or other alternative fuel island ferries are deployed on this line?

The following study comprises of chapters: Methodology, Results and Discussion, Conclusion. Methodology section describes the currently operating ferries and analyses how the energy-transport optimization model was built. In the subsections also operating costs derived from the fuel consumption and GHG emissions are assessed. The results and discussion chapter brings out the findings of the analyse, including its GHG emission reduction and explains its main shortages. The conclusion chapter summarizes the study and points out the main aspects of continuation and future steps.

2. METHODOLOGY

2.1. System Description

The ferry route from the port of Virtsu on the mainland to the port of Kuivastu on the island of Muhu, shown in Figure 1 has the length of 3.7 nm, and depending on the season there are up to 30 daily ferry crossings. The time required for a one-way trip, considering the embarkation and disembarkation time of passengers and vehicles, and the time required for loading and unloading the ferry, is under normal weather conditions 35–45 minutes, with the crossing time not exceeding 28 minutes. The electricity grid in the region will be expanded in near future with a new 330 kV connection, enabling the construction of fast charging infrastructure.

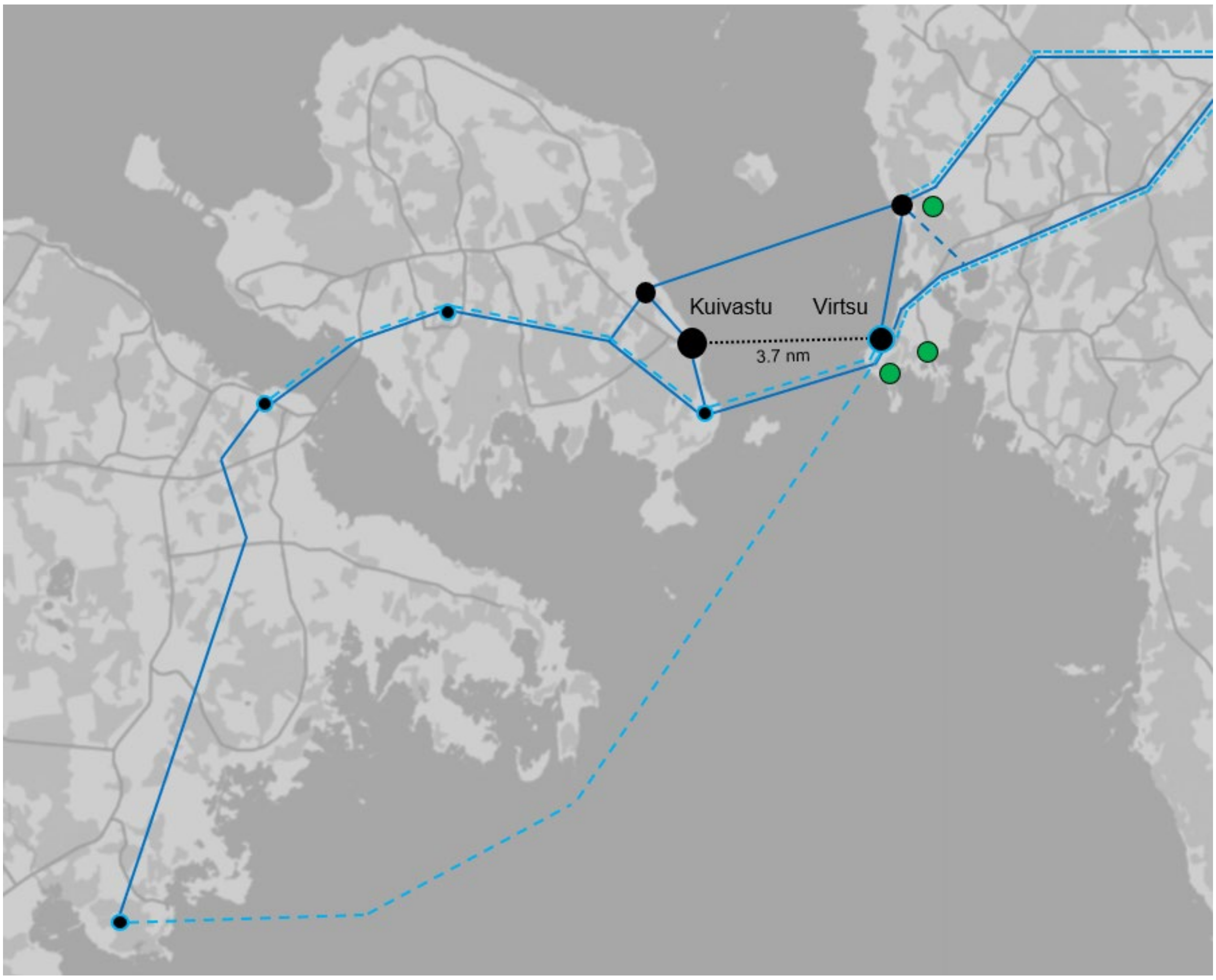

Figure 1 Illustration of the ferry route and the related infrastructure. Legend: port (large black circle), town or other node (small black circle), wind turbines (green circle), ferry route (dotted black line), electricity grid (330 kV: light blue line, 110 kV: blue line; existing: solid, planned: dashed), road (dark gray line). [8]

To evaluate the technical feasibility of the alternative fuel investments, the future energy system development paths must be considered. Currently, electricity charging infrastructure does not exist in the ports of Virtsu and Kuivastu. However, the electricity grid is sufficient for the charging infrastructure after the grid expansion. We assume that the electricity can be sourced at the hourly area price, with an additional transmission fee of 2 c/kWh and port operator margin of 2 c/kWh. The hourly area prices are retrieved from ENTSO-E [9]. For hydrogen, no large-scale green hydrogen production plants currently exist in Estonia. The fuel is estimated to be available in larger quantities and lower costs by 2030 through the Nordic Baltic Hydrogen Corridor [10], but would require an additional road transport step. By 2040, local production or potential expansion of the hydrogen transmission network would make the fuel more directly available for the ports located in the mainland [10]. As baseline value, we assume that hydrogen is available in compressed form at a constant price of 10 €/kg.

Biomethane (CBG) as sustainable marine fuel has several advantages with one of them being an alternative to reduce GHG emissions [11]. The evolution and feasibility of biogas across the world is currently uneven. The development depends on the availability of feedstocks but also on the policies that encourage its production and use. Europe is the largest producer of biogas today [12]. According to the European commission, Estonia can replace about 25% of the current natural gas consumption (imports) with biomethane. Currently, 20% of its sustainable biomethane potential is deployed. Beyond its emission reduction potential, biomethane is also an attractive option due to its availability in Estonia, which is also supported by the rise of production to the target of 100 million m^3 by 2035 [13]. Currently, most of the biomethane produced in Estonia is used in the transport sector and there are several filling stations around the country. For biomethane, we assume the baseline price to be 1.25 €/kg [14].

2.2. Ship Modelling

Currently, there are two sister ferries operating on the Virtsu-Kuivastu line. Depending on the season, the timetable for operating varies with less trips per day during winter period and more trips in the summer period. The double-ended sister vessels Piret and Tõll, the latter shown in Figure 2, were built in 2017. The newbuilt passenger ferries were using conventional marine diesel oil for operating, and in 2019, the ferry Tõll was retro-fit to diesel-electric hybrid. The technical parameters for Tõll are shown in Table 1.

Figure 2 Passenger ferry Tõll.

Table 1 Technical parameters of the reference ferry Tõll.

Parameter	Value
LOA [m]	114
BOA [m]	19.7
Draft [m]	4.0
Gross tonnage [t]	4987
Speed [kn]	15
Main engine	2×1520 kW (MTU 16V400M03)
Auxiliary engine	2×1320 kW (MTU 12V4000M33F)
Battery capacity [kWh]	678
Passenger capacity	700
Vehicle capacity	150

To estimate the fuel consumption of the island ferries, data collection was conducted. The actual schedule data for 2024 was retrieved from the ferry operator. For each voyage, the speed profiles were determined based on minute-level AIS data [15]. Available charging time was estimated by subtracting one minute from the time at port due to charging connection and disconnection. The load profile was estimated based on a reported load example [16], which was time-normalised and divided into three sections following [17]: departure, cruising, and arrival. The instantaneous power consumption P_i was calculated using nominal power consumption P_o, operating speed v_i and its nominal value v_o, operating load x_i, scale factor n and overall efficiency η_{tot}, and auxiliary power consumption P_{aux} as follows:

$$P_i = \frac{x_i}{\eta_{tot}} \cdot P_o \cdot \left(\frac{v_i}{v_o}\right)^n + P_{aux} \quad (1)$$

For overall efficiency, the conversion losses were estimated based on the power conversion system configuration. This resulted in the following efficiency estimations at nominal load: diesel (MDO) 41%, diesel-electric hybrid 38%, hydrogen (H2) 46%, biomethane (CBG) 46% and fully electric (EL) 88%. For simplicity, the auxiliary power consumption P_{aux} was estimated to be constant of 200 kW for all the alternative fuels. Finally, the simulated profiles were aggregated on a ten-minute level, maintaining the correct sequence of information whether the ferry is on route or in port.

In actual operations, power consumption varies due to external factors. One of the most significant in Estonian waters is the presence of ice conditions and low ambient temperatures. Ice conditions increase ship resistance depending on ice thickness, while navigation in ice requires slower speeds and more precise manoeuvring. Icebreaking effort, friction and vibration from ice contact, and heating auxiliary systems substantially increase the energy demand under winter conditions. The applied energy consumption calculation method does not adequately account for these factors, highlighting the need for physics-based simulations in further analyses. In this work, we approximate the influence of ice and weather conditions by scaling the calculated energy consumption with three factors: 1.0 for clear, 1.5 for average, and 2.0 for rough.

2.3. GHG Emissions Data

Life Cycle Assessment (LCA) is a comprehensive methodology which is used in various industry sectors to evaluate the environmental impacts associated with all scopes of a product's life cycle [18]. In maritime industry, this includes energy use and emissions linked to the construction, operating and decommissioning of ships. The EU and the IMO have introduced methodological frameworks [19,20] within the LCA context to support the consistent estimation of Well-to-wake (WtW) GHG emissions. These frameworks are built upon sustainability criterions and GHG emissions reduction targets, aiming to promote the adoption of low-carbon and sustainable alternative fuels on a global scale.

In this study, the theoretical GHG emissions for fuel alternatives are assessed according to the guidelines of FuelEU Maritime [3] by calculating WtW GHG emissions of the LCA. The total GHG emissions include the Well-to-Tank (WtT) emissions of the energy carrier supply and Tank-to-Wake (TtW) emissions of the total fuel use, and can be calculated as:

$$WtW_{GHG} = WtT_{energy\ carrier\ supply} + TtW_{fuel\ use} \quad (2)$$

Electricity generation methods across the countries in Europe vary significantly, for example in Latvia and Sweden electricity is produced from renewable sources of energy, whereas for example in Estonia and in Poland, fossil fuels are the main sources [21]. In the case of using fossil sources for electricity generation, electrification and hybridization may not always be carbon-free solution and might potentially produce significant amount of GHG emissions [22]. Due to the non-renewable sources in electricity production in Estonia, in this study the assessment for fully electric and diesel-electric hybrid ships is not assessed by FuelEU Maritime according to which coefficients in WtT and TtW are not applicable. For electricity, the WtW GHG emissions were assessed with equation:

$$WtW_{GHG} = E \cdot g_{\mathrm{el}} \quad (3)$$

where E is the total energy demand and g_{el} is the electricity emission factor. To represent the current grid electricity, the emission factor was estimated to be 417 g_{CO2eq}/kWh, based on the national electricity production mix in 2024 [23]. A similar method has been used in several earlier studies [24–26]. For an alternative scenario, where the electricity is either (a) primarily sourced from renewable production such as wind power or (b) the production mix in the market area develops and the emission intensity decreases, we considered emission factor equal to the neighbouring market area, i.e. Finland's 32 g_{CO2eq}/kWh [27].

2.4. Techno-economic Model

The economic feasibility of developed scenarios was studied with a linear cost-optimization program, implemented in Pyomo (version 6.8.2) [28] and solved with CBC (version 2.10.11) [29]. The model simulates the ferry operation at a ten-minute resolution and minimizes the objective function:

$$C_{\mathrm{tot}} = \sum_{t=1}^{T} P_{\mathrm{t,MDO}} \cdot c_{\mathrm{MDO}} + n_{\mathrm{charge}} P_{\mathrm{t,el}} \left(c_{\mathrm{t,el}} + c_{\mathrm{grid}}\right) + P_{\mathrm{t,H2}} \cdot c_{\mathrm{H2}} + P_{\mathrm{t,CBG}} \cdot c_{\mathrm{CBG}} \tag{4}$$

which determines the total fuel operating cost C_{tot} from the calculated ten-minute power consumption P_t, fuel cost c, and for the electric configurations, charger efficiency η_{charge}, hourly electricity price $c_{t,el}$, and grid tariff c_{grid}. The alternative fuel configurations were individually simulated with single-parameter sensitivity analysis for on-board fuel storage and, for electric and hybrid-electric ferries, shore charger capacity. The analysis only considers fuel operating costs and excludes capital expenditures for initial investments and component replacements (e.g., battery, fuel cell).

Ferry energy demand was set as a hard constraint, creating an infeasible scenario if the demand was not met for example due to insufficient charging rate or on-board fuel storage capacity. Charging rate limits were imposed for the ferries depending on the alternative fuel: for electricity based on the charger capacity, for biomethane assuming a fast-filling station [30], and for hydrogen assuming shore-to-ship bunkering [31]. Additionally, the on-board fuel storage was initialized at 50% with a cyclic storage constraint, and state-of-charge constraint assumed depending on the alternative fuel: hydrogen 8–100% due to refueling margin [32] and electricity 10–90% to manage battery state-of-health.

3. RESULTS AND DISCUSSION

3.1. Comparison of fuel operating costs

We simulated two representative operational weeks with: a low-demand week with 115 trips and a peak-demand week with 177 trips. To capture operational variability, three energy consumption levels were considered across diesel, fully electric and diesel-electric hybrid scenarios, reflecting the effects of varied ice and weather conditions. For electric and diesel-electric hybrid scenarios, three charger capacities, i.e. 5.0 MW, 2.5 MW and 1.0 MW, were evaluated to account for infrastructure limitations.

Figure 3 presents the estimated reductions in fuel operating costs for the analyzed configurations. In all scenarios, diesel-electric hybrid operation offers cost improvements over diesel. Notably, higher charger capacities enable significantly greater savings, up to 46%, by allowing increased electric operation. However, this benefit diminishes in high-demand scenarios where the operation relies more on diesel. At the lowest charger capacity, hybrid systems even lead to higher costs, that is –5%, due to reduced overall efficiency. Similarly, the fully electric operation is highly dependent on charger capacity. Under the current operating schedules, full electrification is feasible only with the highest charger capacity and is not possible under the high-demand scenario. When feasible, however, fully electric systems provide the greatest cost reductions, i.e. 75–78%, compared to diesel. The small variation is due to higher consumption necessitating charging during more expensive hours. Among indirect electrification options, biomethane and hydrogen are technically feasible across all conditions. Biomethane slightly outperforms the diesel-electric hybrid option, savings being 58%, but in contrast, hydrogen results in a cost increase of 27% relative to diesel, primarily due to the expected high fuel price.

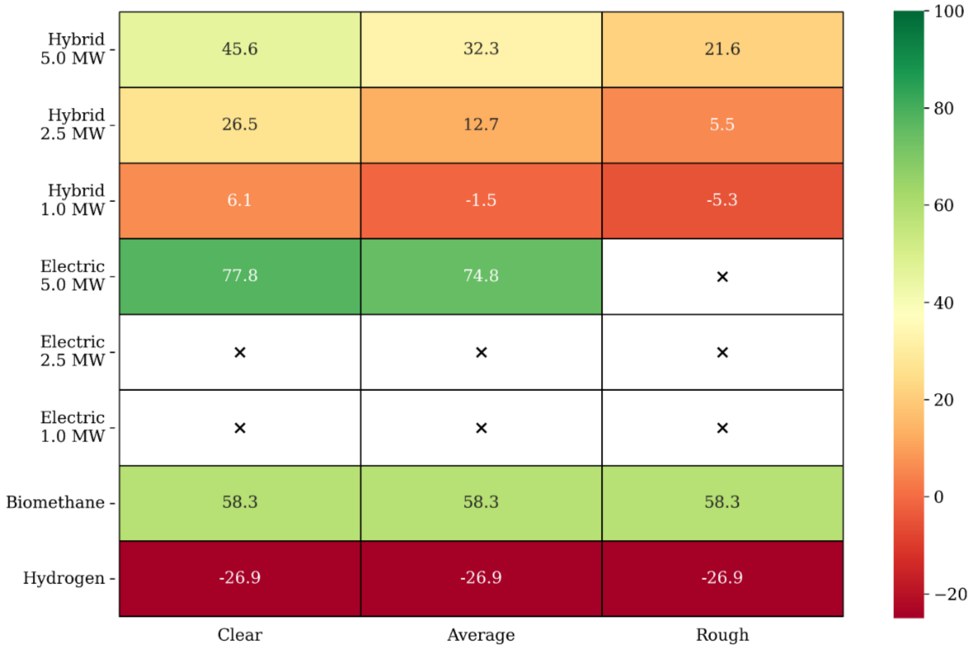

Figure 3 Relative fuel operating cost reduction (%) for different alternative fuel configurations in comparison to diesel-fueled operation for three levels of fuel consumption based on weather conditions clear, average, and rough. Infeasible scenarios are indicated with (x).

3.2. Estimated emissions of alternatives

Figure 4 presents WtW GHG emissions for the simulated period consisting of two representative operational weeks. With diesel, baseline emissions of 139 tCO_2eq are reached. For diesel-electric hybrid configurations, emissions follow the trend of fuel operating costs, depending on charger capacity, which governs the required diesel consumption. With current grid electricity, emissions range from 92 to 141 tCO_2eq; with low-emission electricity, from 37 to 124 tCO_2eq. Similarly, emissions for the fully electric configuration depend on electricity sourcing. With current grid electricity, emissions are 74 tCO_2eq, not significantly lower than for hybrid. However, with low-emission electricity, emissions decrease to 5 tCO_2eq. This represents an optimistic scenario, as Estonia is currently a high-emission electricity market area, and such values are unlikely to be achieved solely through grid electricity in the near term. Hydrogen yields the lowest emissions at 4 tCO_2eq but, as discussed earlier, faces challenges related to fuel availability. The same considerations as for electricity apply, though low emissions are likely due to the required compliance with green hydrogen regulations such as RFNBO [33]. Biomethane also provides a significant reduction, with emissions of 23 tCO_2eq.

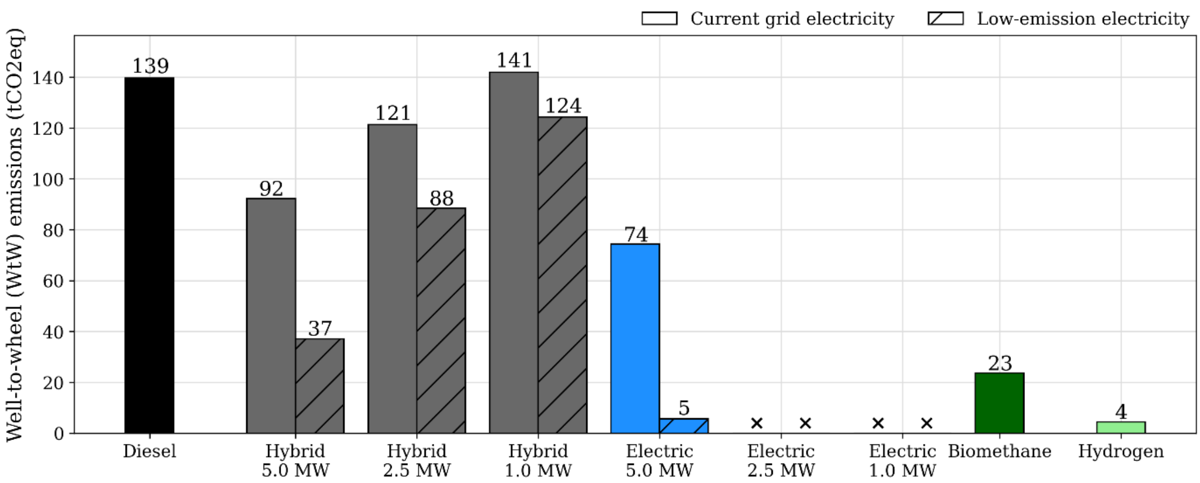

Figure 4 WtW GHG emissions for different alternative fuel configurations in average weather conditions with two alternative options for electricity sourcing. Infeasible scenarios are indicated with (x).

4. CONCLUSION

Battery-electric propulsion systems are gaining increasing attention in various maritime applications due to benefits including low airborne and underwater noise, reduced vibration and low-emission operation. From the perspective of fuel operating costs and GHG emissions, fully electric island ferries appear to be promising option for the studied Estonian route and warrant further investigation. Among the alternative fuels, biomethane offers a more practical option than hydrogen for hybrid configurations due to its availability through existing supply chains. Thus, this study highlights both practical and theoretical implications for the specific route and environment as it brings out challenges and opportunities for low carbon future in realistic aspects.

However, the analysis identified uncertainties that should be addressed in future research. Fully electric island ferries show promise for the studied Estonian route due to low operating costs and emissions. The economic analysis should be expanded to compare investment needs for port-side and onboard systems, and to include sensitivity analyses on key parameters such as electricity and fuel prices. Furthermore, the studied ferry operates in regions partially covered by ice, posing challenges for fully electric operation. Based on the infeasibility shown by the conducted simulations, it remains uncertain whether fully electric vessels can maintain the current schedules under continuous rough weather conditions, highlighting the importance of hybrid system availability. Improving energy consumption estimates under such conditions will require the integration of weather information, e.g., wind and wave conditions, and physics-based simulations.

From the GHG emissions perspective, the fully electric configuration resulted in a 47% reduction in WtW GHG emissions compared to diesel when using current grid electricity. A significantly greater reduction, up to 96%, is achievable under scenarios assuming low-emission electricity. These results underscore both the importance of electricity sourcing and the shortcomings in current GHG assessment guidelines, which vary by country and lack consistency. Electricity generation methods vary widely across EU countries, many of which do not yet rely on fully renewable sources. Consequently, fully electric or diesel-electric hybrid ships operating in different countries may exhibit high WtW GHG emissions despite using the same technologies. This highlights a critical shortcoming in the current guidelines and underscores the need for further development by regulatory bodies such as the IMO and FuelEU Maritime to standardize the evaluation of GHG emissions for fully electric ships.

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ENHANCING JUNIOR DECK OFFICERS PERFORMANCE THROUGH SIMULATOR TRAINING

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Abstract

This paper analyses common errors by junior deck officers in maritime simulator training, emphasizing strategies to enhance navigational safety through improved situational awareness, communication, and teamwork. Research of recorded simulator sessions revealed prevalent mistakes, including misjudging minimum safety distances, misinterpreting navigational signals, lapses in situational awareness, poor communication and lack of effective teamwork. Key variables influencing errors include distraction levels and scenario difficulty. Actions such as targeted training programs, dynamic scenario designs, and coordination exercises, were tested to reduce error rates. Results indicate that structured feedback, collaborative training, and adaptive scenarios significantly improve situational awareness, communication, and decision-making. The study highlights the importance of addressing human factors and experience gaps in maritime training, providing scalable strategies for real-world application. These findings promote safer maritime operations by training young deck officers with new skills to enhance situational awareness and teamwork, reducing navigational incidents.

Keywords: Situational Awareness, Communication, Teamwork, Human Factors, Navigational Safety

1. INTRODUCTION

The maritime industry relies on the competence of deck officers to ensure safe navigation. Junior deck officers, often at the beginning of active service, face significant challenges in mastering the complex interplay of situational awareness, communication, and teamwork required for effective Bridge Resource Management (BRM). These skills are critical to preventing navigational incidents, such as collisions and groundings, which may lead to severe safety, environmental, and economic consequences. The IMO Model Course 1.22 (Ship Simulator and Bridge Teamwork) provides a framework for developing these competencies through simulator-based training, emphasizing the importance of human factors in maritime safety. However, junior officers frequently make mistakes in simulator training, such us misjudging safety distances, misinterpreting navigational signals, and exhibiting lapses in situational awareness, poor communication, and ineffective teamwork. These mistakes, often exacerbated by distractions and complex scenarios, highlight the need for targeted training interventions to bridge the experience gaps and enhance performance.

This paper research the most common mistakes made by junior deck officers during maritime simulator training and evaluates strategies to improve their performance. By analyzing recorded simulator sessions, key mistake patterns and their contributing factors were identified. To address these issues, authors tested interventions including targeted training programs, dynamic scenario designs, and coordination exercises. These interventions aim to enhance situational awareness, communication, and teamwork, aligning with the principles of IMO Model Course 1.22. Our research demonstrates that structured feedback, collaborative training, and adaptive scenarios significantly reduce mistake rates and improve decision-making. These results underscore the critical role of simulator-based training in preparing junior officers for real-world challenges, offering scalable strategies to enhance navigational safety.

The significance of this research lies in its focus on human factors, a primary contributor to maritime incidents. By addressing experience gaps through simulator training, the goal is to educate junior deck officers providing them the skills which are needed to operate effectively within a bridge team, reducing the likelihood of navigational errors. This paper contributes to the maritime training literature by providing evidence-based strategies that can be integrated into existing training programs, promoting safer maritime operations globally.

2. LITERATURE REVIEW

The maritime industry places significant emphasis on the training of deck officers to ensure navigational safety, with simulator-based training being a cornerstone for developing competencies in Bridge Resource Management (BRM), situational awareness, communication, and teamwork, as outlined in the International Maritime Organization's (IMO) Model Course 1.22 (Ship Simulator and Bridge Teamwork) [1]. This literature review examines key studies and publications that address common mistakes by junior deck officers in simulator training and strategies to enhance their performance, focusing on situational awareness, communication, and teamwork. The review synthesizes findings from recent and relevant maritime research to provide a foundation for understanding how simulator training can mitigate human errors and improve navigational safety.

Maritime simulator training is a critical tool for enhancing the navigational safety of young deck officers, particularly in addressing common mistakes in situational awareness, communication, and teamwork. Analyzed research highlights that inexperienced officer often struggle with non-technical skills, which simulator-based training effectively mitigates through structured practice and feedback. Chauvin et al. [2] applied the Human Factors Analysis and Classification System (HFACS) to analyze maritime collisions, identifying situational awareness lapses and communication failures as prevalent among junior deck officers. Their findings underline the need for targeted simulator training to bridge these gaps. Similarly, Ernstsen and Nazir [3] demonstrated that simulator scenarios with increasing complexity significantly improve situational awareness and decision-making among young officers, reducing errors through iterative practice.

Bury et al. [4] explore innovative tools transforming simulator-based situational awareness training for maritime deck officers in their study, The research highlights advanced simulator technologies and methodologies that enhance situational awareness, addressing common errors among junior deck officers. The study emphasizes the integration of adaptive scenarios and real-time feedback in simulators to improve hazard detection and decision-making, contributing to safer maritime navigation.

Sharma et al. [5] investigate situational awareness (SA) requirements for maritime navigation in their study. The research employs a Goal-Directed Task Analysis (GDTA) to identify critical information elements needed by navigators to maintain SA. Based on interviews with seven experienced navigators, the study highlights how lapses in SA, such as misinterpreting navigational data, contribute to errors and proposes simulator-based training to address these issues, enhancing navigational safety.

Fjeld et al. [6] explored how Bridge Resource Management (BRM) training participants perceive non-technical skills, noting that junior officers often misunderstand the importance of communication and teamwork, which simulators help clarify through realistic scenarios. A complementary review by Fjeld et al. [7] highlighted that simulator-based training is particularly effective in developing situational awareness and teamwork, critical for reducing errors in high-pressure maritime environments. Øvergård et al. [8] emphasized the role of effective communication, particularly closed-loop protocols, in enhancing navigational teamwork. Their study found that simulator training fosters accurate and relevant communication, addressing initial high error rates in team coordination

Sellberg [9] focused on the instructor's role in simulator training, emphasizing that structured briefings and debriefings are essential for correcting situational awareness and teamwork errors among novices. Wiig et al. [10] used topic modeling to trace conceptual developments in maritime simulator training, identifying a shift toward integrating non-technical skills like hazard identification and communication into curricula, which significantly benefits inexperienced officers.

These studies collectively affirm that simulator training provides a controlled environment to address common errors, such as neglecting visual lookout and poor task delegation, through repeated exposure and feedback. By simulating complex scenarios, training programs enhance junior deck officers' ability to integrate technical and non-technical skills, ultimately improving navigational safety and operational efficiency. Future research should explore optimal scenario designs to further reduce persistent errors in situational awareness and communication.

3. OBSERVATIONAL AND EXPERIMENTAL ANALYSIS OF SIMULATOR TRAINING SESSIONS

The research utilized the Transas NTPro full-mission simulator, known for its accuracy in simulating real-world maritime navigation conditions, certified by Det Norske Veritas (DNV) and compliant with STCW requirements [11]. The research was performed within a five-day of Ship Handling and Maneuvering Simulator Course, designed following STCW requirements and IMO Model Course 1.22. A total of six Ship Handling and Maneuvering Simulator Courses were recorded with a total of 24 participants. In the research were included only junior deck officers with less than one year of sea experience in junior rank, ensuring a homogeneous sample with comparable navigational backgrounds. All participants were familiar with the simulator's controls, minimizing the influence of technical inexperience on performance outcomes.

The applied methodology combined observational analysis with experimental interventions to evaluate and improve the performance of junior deck officers. In performance of each Ship Handling and Maneuvering Simulator Course were participated four junior deck officers. Each simulator exercises involved a bridge team composed of three participants acting as the Master, Officer of the Watch (OOW), and Helmsman. One of course participant was assigned as an observer to monitor team dynamics and individual actions. The observer role was critical mostly for documenting specific behaviors and mistakes without influencing the team's operations. Observer notes were used in post-session debriefs. In each subsequent simulator exercise, the participants changed their roles. Each session lasted 50 to 60 minutes, during which participants navigated scenarios of increasing complexity. On the first day, scenarios were deliberately simple to establish a baseline, with difficulty progressively increased to include challenging conditions such as high traffic density and time-critical decision-making tasks by the fifth day. The final day included an assessment session for each candidate, designed to evaluate their ability to integrate skills learned throughout the course under realistic conditions. On the final day, every candidate operated similar vessel as on his last contract at sea (model of product tanker, Aframax tanker or bulk carrier).

The instructor recorded key variables influencing performance, focusing on common mistakes identified in prior research: inadequate passage planning, neglecting visual lookout, misinterpreting data from radar, ECDIS, and AIS, poor hazard identification, ineffective decision-making under stress, poor closed-loop communication, hesitation to speak up, improper VHF radio communication, inadequate task delegation, and underutilization of team resources. These variables were selected as former research indicated their direct impact on navigational safety and their prevalence among young deck officers. The simulator exercises were purposely designed to induce a stressful and emotionally demanding situation characterized by high workloads and time-sensitive decisions, to test participants' situational awareness, leadership, communication, and teamwork under pressure.

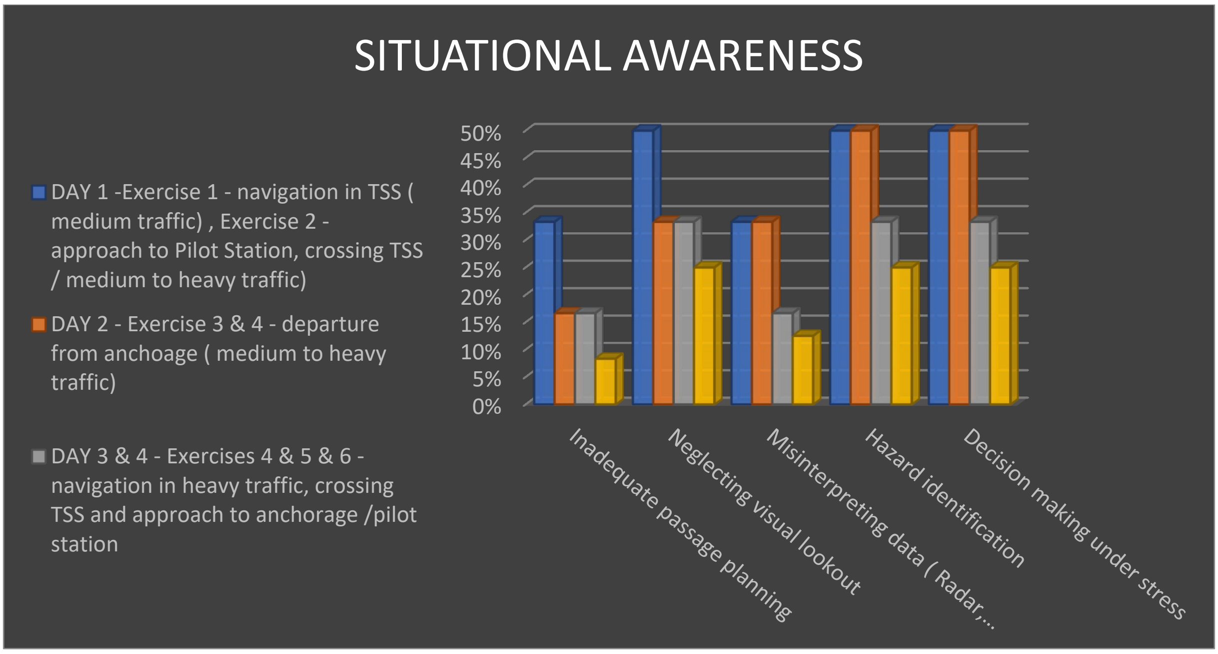
The relatively small sample size of 24 participants over the total of six Ship Handling and Maneuvering Simulator Courses was justified by availability of junior officers with similar sea experience, ensuring consistency in baseline navigational knowledge. The course structure facilitated both individual skill development and team-based coordination. Each day of the course scenarios were tailored to progressively challenge skills of participants, with dynamic elements such as unexpected vessel traffic or equipment malfunctions introduced to simulate real-world unpredictability. Structured feedback was provided after each session, focusing on specific mistakes and offering actionable strategies for improvement. Collaborative exercises, such as role-switching between Master, OOW, Helmsman and Observer, were incorporated to enhance teamwork and communication skills. Adaptive scenarios adjusted in real-time based on participants' performance, ensuring that research remained challenging yet achievable. The observational component relied on detailed session recordings, capturing both quantitative metrics and qualitative insights.

4. ANALYSIS OF OBSERVED MISTAKES IN SIMULATOR TRAINING SESSIONS

The observational data collected from simulator sessions using the Transas full mission NTPro simulator during a five-day Ship Handling and Maneuvering Simulator Course provides valuable insights into the performance of junior deck officers with less than one year of sea experience. The recorded mistakes rates across three key categories: situational awareness, communication, and teamwork, highlight prevalent challenges and the effectiveness of progressive training in reducing mistakes. The data tracks mistake percentages across exercises, with scenarios increasing in complexity through research duration.

4.1. Situational Awareness

Situational awareness mistakes were prominent, particularly in the introductory scenarios. Inadequate passage planning was observed in 33% of cases during Exercises 1 dropping to 8% by the final exercise at Day 5. This improvement suggests that structured training and feedback helped participants refine their planning skills. Neglecting visual lookout was a notable, with 50% mistake rates in beginning, reducing to 25% by the final exercise. This persistent challenge underscores the tendency of junior and unexperienced officers to over-rely on electronic systems like radar, ECDIS, and AIS, which also showed high mistake rates in misinterpretation (33% in Exercise 1, 13% in the final exercise). Hazard identification mistakes mirrored this trend, decreasing from 50% to 25%, while decision-making under stress was reduced from 50% to 25%. These reductions indicate that repeated exposure to high workload scenarios and targeted training enhanced participants' ability to maintain awareness and make proper decisions.

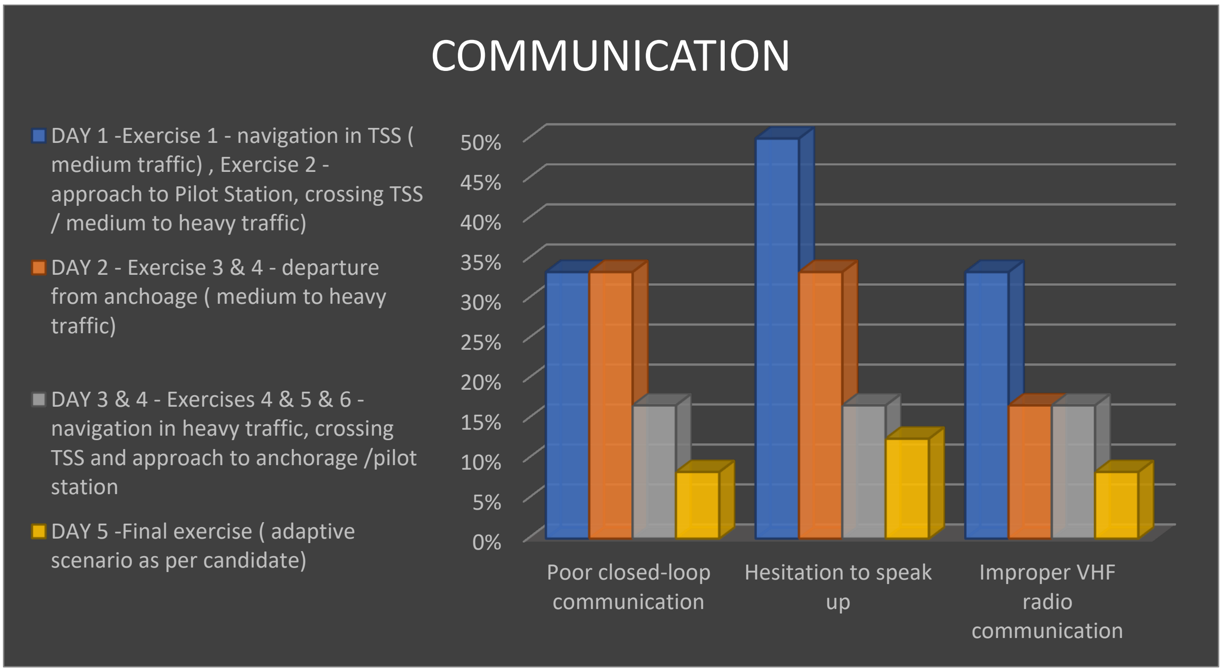


Graph 1 Situational awareness mistake rates

Source: Author's own work

4.2. Communication

Communication mistakes were notably high in early exercises but showed significant improvement. Poor closed-loop communication, critical for ensuring instructions are understood and executed, occurred in 33% of cases in Exercise 1, dropping to 8% by Day 5. Hesitation to speak up was equally prevalent (50% in Exercise 1), improving to 13% in the final exercise, suggesting that collaborative exercises and role-switching fostered greater confidence. Improper VHF radio communication was less frequent, starting at 33% and reducing to 8% by Day 5, likely due to focused training on standard protocols. These improvements highlight the effectiveness of structured feedback and practice in addressing communication gaps, which are critical for safe navigation.

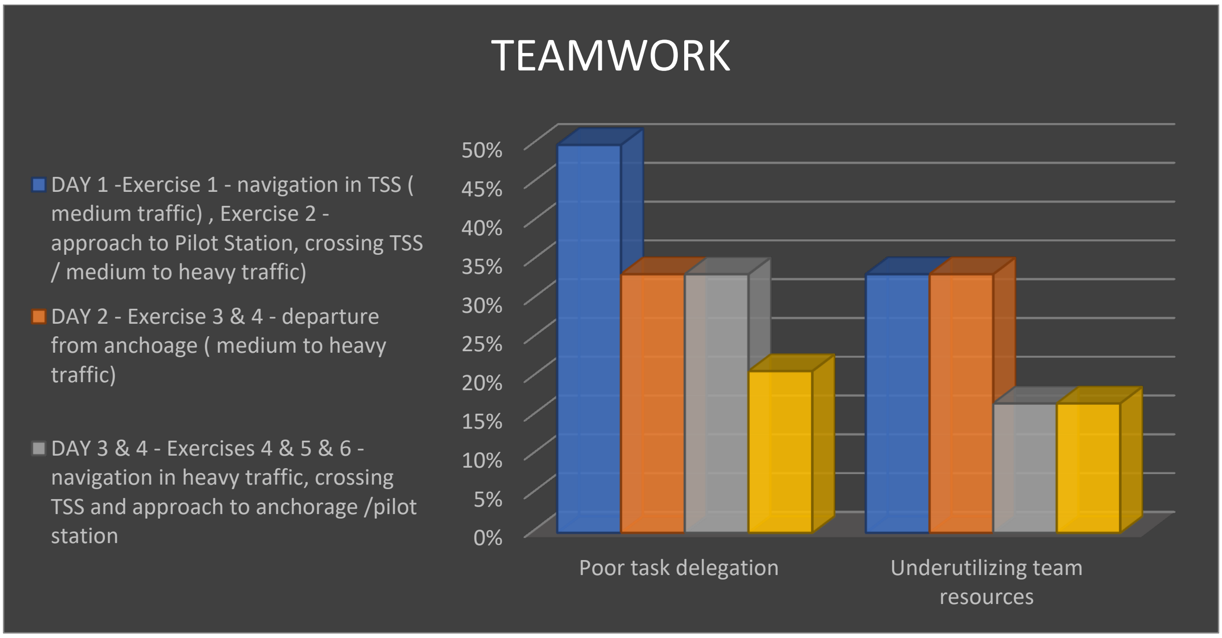


Graph 2 Communication mistake rates

Source: Author's own work

4.3. Teamwork

Teamwork deficiencies were the most pronounced initially, with poor task delegation observed in 50% of cases in Exercise 1, decreasing to 21% by Day 5. Underutilization of team resources dropping from 33% to 17%. These high initial error rates reflect the inexperience of junior deck officers in leveraging team dynamics under stress. The reduction suggests that exercises emphasizing role clarity and coordination were effective in enhancing collaborative skills.



Graph 3 Teamwork mistake rates

Source: Author's own work

5. TRAINING TOOLS AND METHODOLOGIES USED TO ENHANCE YOUNG DECK OFFICERS' PERFORMANCE

Prior to the simulator exercise, junior deck officers underwent theoretical lecture to pinpoint most common mistakes in situational awareness, communication and teamwork. Each officer was evaluated individually and as part of a bridge team, with performance metrics focusing on passage planning accuracy, lookout effectiveness, data interpretation from radar, conning monitor, ECDIS, AIS, hazard detection, communication clarity and task delegation.

After every simulator exercise, participants engaged in debriefs to review mistakes, received targeted feedback on their performance, and practiced refined skills in follow-up simulator scenarios designed to reinforce learned techniques and improve their overall competence. Observer's written notes of specific mistakes during the simulator exercises were also taken into account.

To mitigate mistakes made by junior deck officers in the identified categories, targeted tools and strategies were implemented during within 5-days simulator-based training. Below are specific tools tailored to each mistake category based on general maritime training best practice.

Situational Awareness

Inadequate Passage Planning: Incorporated pre-briefing sessions to emphasize route analysis, waypoint selection, and contingency planning and use of standardized passage planning templates.

Neglecting Visual Lookout: Conducted visual lookout drills emphasizing visual cues such as small vessels and buoys, to reinforce the importance of continuous lookout.

Misinterpreting Data (Radar, ECDIS, AIS): Used real-time feedback during simulator sessions to highlight misinterpretations, with post-session debriefs to review mistakes.

Hazard Identification Error: used adaptive simulator scenarios with escalating risks to train officers in early hazard detection and prioritization.

Decision-Making Under Stress: designed high workload simulator scenarios with time-critical decisions to build resilience.

Communications

Poor Closed-Loop Communication: reinforced closed-loop techniques. Trained officers in structured communication protocols, emphasizing clear instruction, acknowledgment, and confirmation.

Hesitation to speak up: used role-switching exercises in the simulator to empower officers to voice concerns, regardless of rank.

Improper VHF Radio Communication: provided feedback on clarity, brevity, and adherence to protocols, with repeated practice to correct errors.

Teamwork

Poor Task Delegation: rotated roles (Master, OOW, Helmsman) in simulator sessions to build understanding of task delegation needs. Used debriefs to discuss effective delegation strategies.

Underutilizing Team Resources: Designed simulator exercises requiring teamwork, such as emergency maneuvers, to encourage resource utilization. Used structured debriefs to discuss team resource use.

6. CONCLUSION

Simulator training has proven to be a valuable tool in enhancing the performance of junior deck officers, addressing critical skill gaps through structured practice and feedback. The data reveals that while young deck officers initially struggled with situational awareness, communication and teamwork, targeted training noticeably reduced mistake rates by final day. The training considerably improved junior deck officers' abilities in passage planning, communication and teamwork. Persistent challenges, such as neglecting visual lookout, decision making under stress and hazard identification suggest areas for further focus in training programs. These findings underline the importance of simulator-based training in bridging experience gaps, enhancing navigational safety, and improving skills critical for real-world maritime operations

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MARITIME FINANCE ADAPTATION (MAR FIN ADAPT): A BLENDED FINANCE APPROACH TO MARITIME CLIMATE RESILIENCE AND SUSTAINABILITY

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Abstract

The maritime sector is facing rising sea levels, extreme weather events, and ecosystem deterioration, but these threats hardly offer any support through target resilience finance. Mar Fin Adapt is an innovative data-based strategic finance framework to quantify public, private, and philanthropic revenue flows against systemic funding gaps. Applying environmental and financial datasets with a coastal vulnerability index, climate exposure metrics, and investment flow analyses will facilitate correlations between statistically significant outcomes and risk reduction and nature-based adaptation investment. Pilot application with the framework across five coastal regions resulted in a score improvement of 25 and 30 percent, or an efficiency of over 60 percent of disbursement toward high-resilience-score projects. Blended finance mechanisms achieved an average risk offset of 40 percent to enhance private sector participation. The model further enabled intersectoral collaboration and shaped three policy recommendation drafts. Such results confirm that data-aligned and adaptive investment pathways could statistically improve resilience outcomes by simultaneously increasing access to affordable funding for vulnerable maritime communities.

Keywords: Resilient coastal infrastructure, Maritime Climate, Vulnerable coastal communities, Mar Fin Adapt, Flexible mixed-funding model.

1. INTRODUCTION

The marine sector stands out as uniquely vulnerable due to climate change; threats such as sea level rise, extreme weather conditions, and ecosystem degradation are triggering this vulnerability. In the process, these threats directly pose a serious threat to the maritime industry's infrastructure and operations and to the very livelihood of coastal communities. With a burgeoning recognition of these risk factors, however, a significant gap still exists where dedicated financing mechanisms are absent for climate adaptation in the maritime dialogue. Conventional financing options find difficulty in catering to the needs of flexible, innovative, and nature-based solutions presented in different forms and perspectives based on the specificities of marine environments.

Addressing this financing gap has led to strategizing to ensure resources are efficiently mobilized. Adequate financing remains paramount for developing nations in strengthening the climate resilience of seaports, key nodes in global trade, and the blue economy (UNCTAD, 2022). Without adequate financing directed specifically at this matter, these developing countries may find it difficult to implement adaptation measures, further deepening their vulnerabilities and hindering their sustainable development goals.

Also, this is resiliency as far as maritime is concerned. It would become pertinent infrastructure, ecosystem protection, continuity in the global supply chains, and economic stability. Seaports, shipping routes, and coastal facilities are integral to international trade, and disruption could result in a ripple effect across economies worldwide. It can be improved by adapting or constructing unnatural barriers, reinforcing infrastructure, restoring natural barriers such as mangroves, and developing early warning systems for extreme weather events (Reuters, 2024). Such recent initiatives underscore the need for making climate resilience a mandatory part of maritime planning. One example is the demonstration by Commonwealth nations in Samoa at their meeting to include ocean protection and adaptation to climate change as critical aspects of their declaration. They recognized the need for a concerted effort to save marine biodiversity despite intensifying climate threats while pursuing sustainable economic development (Reuters, 2024).

And blended finance is emerging as one of the most excellent instruments to amend this gap in financing against climate adaptation and probably one of the most amazing forms in bridging these financing gaps for high-risk investment modalities like maritime. Blended finance- the strategic use of public and philanthropic funds to induce private capital investment by risk-mitigation and return-enhancement- could be an appropriate instrument in this respect. It combines different sources of finance to fund a project that might not otherwise be considered viable.Every stakeholder in blended finance has interests at the core of the successful application in such maritime projects. Some ingredients should include identifying a potentially viable revenue stream, regulatory support, and sound governance frameworks. Projects must ensure that they are targeted to provide quantifiable environmental and social benefits and that these are somehow commensurate with investors' returns. Such a process would need to involve governments, financial institutions, and local communities in co-creating something that impacts and is financially sustainable (Economist Impact).

1.1. Key Contributions of the Research

- The research proposes a new hybrid funding model integrating public, private, and philanthropic sources, specifically targeting the maritime sector. The proposed framework identifies and addresses existing financing gaps for climate resilience by aligning investor interests with longer-term sustainability goals.
- Through investments in nature-based solutions and infrastructure that support vulnerable coastal communities, the study added to practical pathways for strengthening marine ecosystems and socio-economic resilience to climate change.
- The research presents an evidence-based framework that integrates environmental, financial, and stakeholder data to formulate adaptive financing models that can be scalable and replicable to support informed decision-making in planning for climate adaptation in the blue economy.

The outline of the paper chapter-wise is as follows. Chapter II is a review of the related literature, while the purpose of Chapter III is to give a brief view of the theoretical framework, key concepts, and methodologies. Chapter IV is going to evaluate the experimental result. Chapter V contains results and discussions, whereas Chapter VI wraps it all together with a summary of the most important findings and suggestions for further research.

2. LITERATURE REVIEW

(Lau et al., 2024). This paper reviews 735 articles from 1997 to 2023 to understand maritime transport resilience research holistically. There were significant findings from the study, which include major themes such as environmental risks, economic obstacles, and safety problems. The authors write that appropriate proactive strategies must be implemented to develop maritime transport systems' resilience. They advocate for cross-disciplinary work and incorporation of sustainable development goals to address this challenge across the broad spectrum of marine affairs (Brown, 2022). They suggested a research agenda for developing resilient frameworks and policies regarding climate change and potential disruptive factors in the future (Rebelo, 2020).

(Akpinar & Özer-Çaylan, 2023). The research results indicate that strategic resilience management, competitive advantage, and supply chain integration are keywords that can be used to improve an organization's adaptability in the specific circumstances of the maritime field (Whittaker et al., 2024). Building a resiliency model to climate-induced disruptions cannot be done without further empirical work, as this study identifies gaps in what already exists in the literature, particularly with regard to how to implement resilience strategies in a maritime operation (Bovino & Niesten, 2021). Yildiz et al., 2023 the authors researched the impact of financial development on marine living resources in Europe from 2009 to 2020, utilizing an assortment of econometric models. While economic development, the study finds, might temporarily impair marine resource sustainability, in the long run, it is supportive. The authors recommend that a well-designed financial system is necessary to support investment into sustainable marine practices that will further enhance the resilience of the blue economy (Biermans et al., 2023).

Mukhtasor et al., 2023, have studied the application of Islamic blended finance in the renewable energy sector in Indonesia. These have determined the significant challenges in financing: high investment costs, long payback periods, and the high-risk perception of investors (Moses & Tafadzwa, 2025). The authors have shown that through an integrated Islamic blended finance model, the most excellent way to mitigate these challenges is by blending public, private, and philanthropic funds to accelerate the country's transition to renewable energy sources (Huang, 2025). The research emphasizes that customized blended finance structures can efficiently address sector-specific financial barriers. Burnham, 2022 argued that a blended finance framework is suitable for urban regeneration led by heritage. The research showed how combining public funds, private investments, and philanthropic contributions can rejuvenate urban areas while being conscientious about cultural heritage. Such a framework aims to attract various funding sources aligned with the interests and priorities of diverse stakeholders so that urban development can be sustainable in a way that respects the historical context (Islam & Sarker, 2022).

Pascal et al. (Tirumala & Tiwari, 2022) observed innovative financing mechanisms for projects related to the blue economy, stressing the importance of adequate valuation methods and performance monitoring for nature-based solutions. They flagged barriers to these initiatives, such as limited access to capital, high perceived risks, and a heterogeneous choice of financial instruments for marine projects. The study proposes that developing tailor-made financial tools and frameworks will ultimately assist private investments in maritime adaptation initiatives (Shirai, 2022).

OECD et al. (Dembele et al., 2022) surveyed blended finance funds and facilities, showing that blended finance works effectively in several areas, such as energy and infrastructure, but has not yet been widely used in projects within the maritime sector (Velentza, 2023). The report identifies opportunities for broadening blended finance within the marine industry, including closing data gaps, improving risk mitigation strategies, and building stakeholders' collaboration. It emphasizes that specific financial instruments tailored to promote sustainable maritime development are critical (Polydoropoulou et al., 2024).

3. METHODOLOGY

3.1. Data Collection and Analysis for Resilience Assessment

The research adopts a multidimensional approach in analyzing climate resilience in the maritime sector, bringing on board environmental, financial, and stakeholder information. First, comprehensive datasets from primary and secondary sources, such as projections on rising sea levels and storm frequency, investment flows, and stakeholder perceptions, will be collated (Monios & Wilmsmeier, 2020). The environmental data shall be obtained from reputable sources such as the IPCC, NOAA, etc.. In contrast, finance data shall be drawn from maritime institutions and blended finance initiatives into a bank for government reporting. Stakeholder input will be obtained from structured surveys and interviews with port authorities, insurers, shipping firms, and community-based organizations (Stockbruegger & Bueger, 2024). A Climate Vulnerability Index (CVI) framework for assessing vulnerability would involve exposure (geographical risks), sensitivity such as age/type of infrastructure, and adaptive capacity such as emergency preparedness and institutional support. Furthermore, GIS tools will be used to spatially map the CVI scores and identify possible resilience gap scenarios (Jawara & Johansson, 2025).

Based on the vulnerability assessment, the Blended Finance Assessment Matrix (BFAM) will be produced to assess the feasibility of mixed financing models for climate adaptation projects. The matrix considers the risk-sharing capacities of public and philanthropic funding against the investment readiness of proposed solutions (e.g., nature-based infrastructure) and the scaling applicability of the interventions. With this modeling scenario of comparative systems dynamics or agent-based simulations, it will be possible to derive clear outcomes for possible scenarios through a wide range of conditions like business as usual, policy-inspired, or finance-led pathways. In doing so, it should assist in deriving the best funding structures and policy alignments that enable inferential adaptability for coastal and maritime systems. Through collaborative, cross-sectoral, and data-driven approaches, this would provide a strong framework for resilience assessments and pathways to practice. It encompasses a blended finance strategy to establish, through both public, private, and philanthropic capital, a venture related to climate-resilient investments on the maritime front. Traditional financial institutions are risk-averse and do not fund nature-based or innovative climate solutions. This approach seeks to bridge these gaps: concessional public and philanthropic funds finance de-risking investments, creating conditions attractive to private-sector participation.

This collaboration is also cross-sectoral in empowering government, industry, finance, and civil society stakeholders to develop resilient marine adaptation strategies jointly. These partnerships will facilitate knowledge transfer, enhance project scalability, and ensure that the solutions are context-specific and replicable. The framework also supports replicable models that can be scaled across those geographical regions with similar climate vulnerabilities to foster sustainable development in the blue economy.

3.2. Data Method

This model proposes decisions through various information sources and sectors to prioritize projects that will benefit greatly. Data used for this decision-making are climate vulnerability assessments, which evaluate marine and coastal systems' exposure, sensitivity, and adaptive capacity to climate hazards such as sea-level rise, extreme weather events, and ecosystem degradation. Blue Economy Investment Trends- The analysis assesses past and present investment flows, investors' behaviors, and risk-return profiles in maritime and coastal development sectors.

Stakeholder and Investor Analysis- the interests, incentives, and risk tolerances of public agencies, private firms, impact investors, and community-based organizations.Adaptation funding pathways from synthesizing all these datasets were defined-aligned financial roadmaps, in short, disbursing capital where it will yield projected impacts of climate change. This should direct resource allocation away from those significant lighting strikes of projects, particularly pursuing those financially workable projects that will assure long-term climate resilience for needy coastal communities.

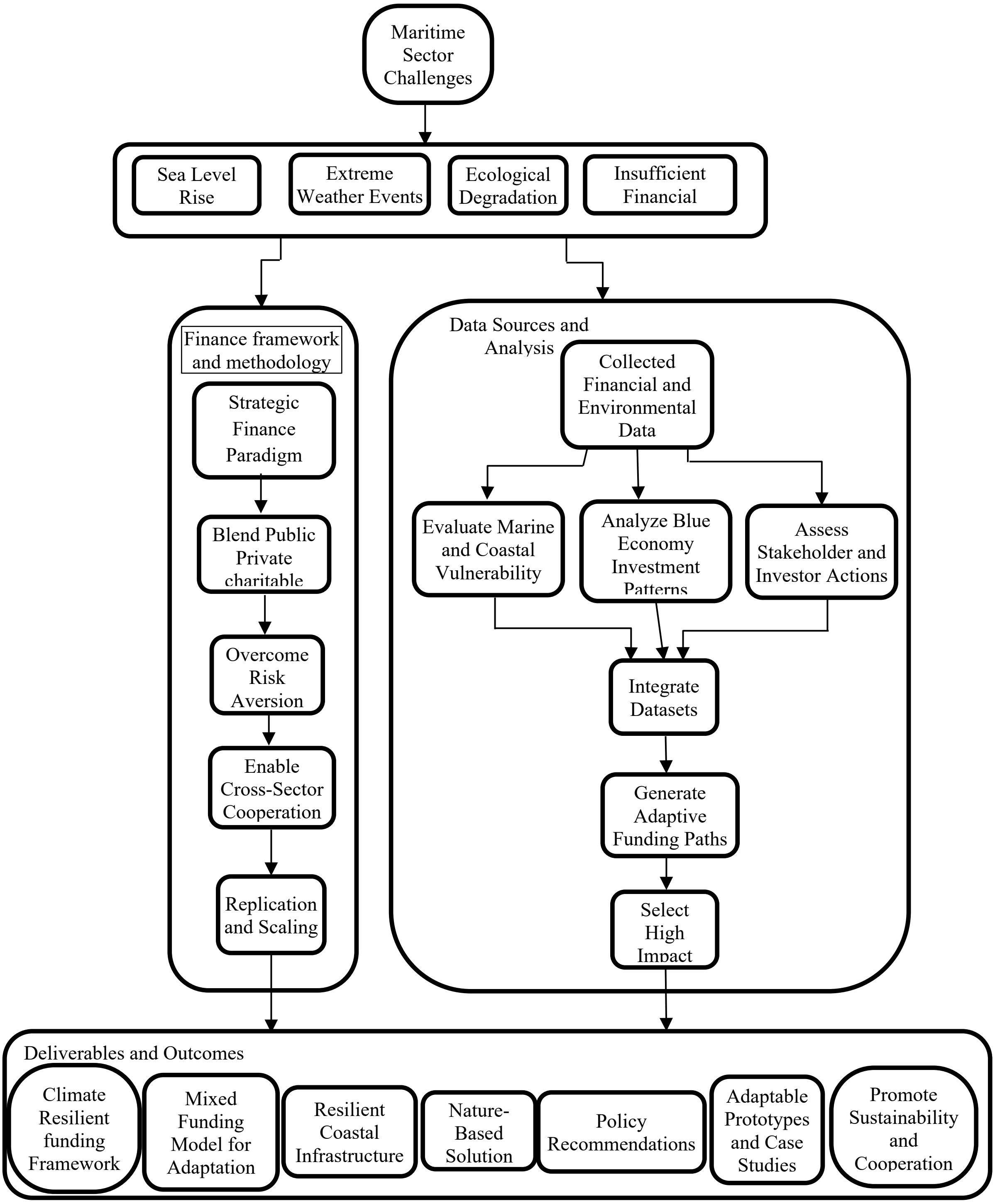

Figure 1 Mar Fin Adapt: A Strategic Framework for Climate-Resilient Funding in the Maritime Sector

Source: Author's own analysis

Figure 1 The approach is captured in the "Mar Fin Adapt" framework, which is a holistic approach addressing the climate-related challenges of the maritime sector, namely sea level rise, extreme weather events, ecological degradation, and restricted funding avenues. The model is based on two main pillars: finance methodology and data analytics. In finance, we propose an optimal blend of public, private, and philanthropic capital which helps in minimizing risk aversion and promotes cross-sectoral collaboration leading to scalable outcomes. On the data analytics side, past and present environmental and financial data are collected and integrated to assess vulnerabilities, investment trends, and formulate funding strategies.

Both these approaches together will lead to concrete and impactful outcomes such as resilient infrastructure, nature-based solutions, adaptive prototypes, and science-based policy recommendations that enhance sustainability and cooperation among stakeholders.

3.3. Framework for Implementing Blended Finance Solutions in Maritime Climate Resilience

Much like climate resilience in the maritime sector, blended finance is an approach for addressing multifaceted problems requiring a serious injection of money. Therefore, some structured procedures can be put in place to facilitate the application of blended finance solutions for maritime climate resilience. The rest is a detailed description of this framework for implementing such solutions for this sector.Blended finance solutions for climate resilience in the maritime sector need a structured methodology to effectively mobilize resources, mitigate risk, and align the interests of all stakeholders involved. This takes a stepwise approach to ensure that projects are impactful, scalable, and financially sustainable.

Stakeholder Mapping and Engagement: The first step would be to identify and engage the relevant key stakeholders from the public, private, and philanthropic sectors. The stakeholders' analysis will provide a thorough mapping of the relevant actors to ensure their becoming aligned with the project goals. Early stakeholder engagement through workshops and consultations will enhance collaboration, build trust, and clarify objectives and contributions for each actor. Therefore, communication channels should be transparent to ensure ongoing discussion and decision-making throughout the process.

Vulnerability and Climate Risk Assessment: Next on the list is an evaluation of climate-related vulnerabilities and risks in the shipping industry. This involves appraisals of the threats posed by climate changes to coastal communities and marine ecosystems as well as port, shipping lanes, and related coastal infrastructure. Such assessments would help in localizing environmental data collection regarding sea-level rise, extreme weather events, or ecological degradation in identified areas under the most threat. Respective results of this assessment will, thereafter, prioritize investment areas and channel resources toward the most vulnerable sectors. Public finance will almost always be utilized for de-risking the investments and thus making them attractive for private investors. Moreover, risk mitigation instruments- such as guarantees or insurance- would be developed for lowering the perceived risks for the investors. The blended finance mechanism is ultimately about a blended value proposition for all stakeholders, combining financial returns with longer-term goals of climate resilience.

Structuring financial products to support identified projects comes next: The diverse financial instruments set up are green bonds, climate resilience bonds, equity financing, etc., according to needs of different investors. IF use pay for performance instruments, wherein pay-out is related to actual resilience outcomes, for instance, successful restoration of a specific area of coastal habitat or reduced risk of flooding. Such projects should prove more effective to secure attractive capital, as they align investor interests with long-term climate resilience objectives. Monitoring and evaluation, followed by adaptation: As soon as a project is discussed, it must put into place a strong monitoring and evaluation (M&E) system to verify how the blended finance model defines progress and success.

KPIs will be developed to measure the success of the projects in terms of environmental impact and financial performance. Periodic evaluations of the impact will keep the projects to task and allow an adjustment whenever necessary. From there, a feedback mechanism will be generated to inform potential changes to the financing approach and to enhance outcomes of later projects. Capacity Building and Knowledge Sharing: Another key methodological component will enable stakeholders to develop their capabilities to manage and implement blended-finance projects well. It will include training workshops and capacity building for local governments and financial institutions, among others, on the blended-finance projects.Knowledge-sharing platforms would be created for these stakeholders to exchange best practices, lessons learned, and new ideas for solutions. This will ensure that local entities acquire the necessary skills and knowledge to successfully manage projects and funding mechanisms.

Scale Up and Replication: Other aspects of the scaling up and replicating such models to other vulnerable regions will be considered once success stories are mapped. Success and impact of blended finance will be shown by way of developing case studies and best practice documentation. The lessons drawn will help forge the pathways for the scaling up strategies that are supposed to involve the international organizations and other funding bodies in the replication of the model in other coastal areas. By scaling successful projects, the blended finance model can then be made to have a larger overall punch in reaching even more at-risk regions.

3.4. Proposed Mathematical Formulation for Blended Finance Solutions in Maritime Climate Resilience

It will mathematically model things like investment allocation, risk minimization, and financial returns towards implementing a blended finance model for ensuring maritime resilience against climate change. Hence, their formulations would include optimizing a capital stack, modeling risk-sharing mechanisms, and estimating the out-turns for different sources of funding.

Maximizing Contribution of Funding Sources Toward Resilience Benefits of Climate While Balanced Contributions by Public, Private, and Philanthropic Funding.

Total Investment Equation

Ctotal = Total capital required

Cpublic = Public/government funding

Cprivate = Private sector investment

Cphilanthropic = Philanthropic or donor funding

$$Ctotal = Cpublic + Cprivate + Cphilanthropic \quad (1)$$

Objective Function

Max I, the total impact of the entire project. This includes the financial return and climate resilience benefits.

Let:

F = Expected financial return

R = Climate resilience benefit (e.g., protection against sea-level rise, ecosystem improvement)

α,β = Weights given to financial return and resilience respectively (based on priority)

$$Maximize\ I = \alpha F + \beta R \quad (2)$$

Risk Mitigation Factor

Let M be a risk-reduction score assigned for investors as per support from public and philanthropic funds.

$$M = \frac{Cpublic + Cphilanthropic}{Ctotal} \quad (3)$$

This would ensure that the higher the share of non-commercial funding, the lesser the risk perceived by private investor.

Constraints

Cpublic ≤ Public Budget Limit

Cprivate ≥ Minimum Private Contribution

F≥ Acceptable Return Threshold

This uncomplicated structure is intended to help in planning and assessing blended finance projects by striking the balance between funding sources, achieving maximum impact, and ensuring a low risk for private investors while realizing long-term resilience goals.

Algorithm: Mar Fin Adapt – Blended Finance Allocation

```
Data Collection:

// Step 1
LOAD climateVulnerabilityData
LOAD blueEconomyInvestmentData
LOAD stakeholderInvestorProfiles

// Step 2: Identify Projects
DEFINE ProjectList = [Project1, Project2, ..., ProjectN]
FOR each Project in ProjectList DO
  CALCULATE ResilienceScore(Project)
  CALCULATE FinancialReturn(Project)
  CALCULATE RiskLevel(Project)
END FOR
// Step 2

// Step 3
SET PublicFund = input amount
SET PrivateFund = input amount
SET PhilanthropicFund = input amount
CALCULATE TotalFund = PublicFund + PrivateFund + PhilanthropicFund

// Step 4: Identification of Risk Mitigation Factor

CALCULATE RiskMitigationFactor = (PublicFund + PhilanthropicFund) / TotalFund

// Step 5: Score Projects
FOR each Project in ProjectList DO
  SET I = α * FinancialReturn + β * ResilienceScore - γ * RiskLevel
  ASSIGN Score(Project) = I
END FOR

// Step 6: Rank and Select Projects
SORT ProjectList BY Score DESCENDING
DEFINE SelectedProjects = []
SET TotalAllocated = 0

FOR each Project in ProjectList DO
  IF TotalAllocated + Project.Cost ≤ TotalFund THEN
    ADD Project to SelectedProjects
    TotalAllocated = TotalAllocated + Project.Cost
  END IF
END FOR

// Step 7: Allocation of Blended Finance
FOR each Project in SelectedProjects DO
  ALLOCATE funding portions from Public, Private, and Philanthropic sources
  DEFINE ImplementationPlan(Project)
END FOR

// Step 8: Monitor and Adapt
FOR each Project in SelectedProjects DO
  MONITOR performance metrics
  UPDATE data inputs by: 78
```

4. EXPERIMENTAL RESULTS

The Mar Fin Adapt blend finance framework has delivered very progressive results regarding investment flows aligning with climate resilience in the maritime sector. From its scenario analyses and modeled funding simulations with multi-source datasets, the following conclusions were drawn:

4.1. Greater Funding Allocation to Resilient Projects:

In the final model, a larger portion of investment could then be directed toward nature-based solutions, resilient coastal infrastructure, and community-based adaptation programs. Long-term-impact projects with greater resilience scores benefited from funded prioritization- even in cases when traditional financial returns were modest.

4.2. De-risking Through Capital Mixing

By blending philanthropic and public capital into project financing, risk gotten substantially reduced on flag-ship adaptation projects thereby opening-up for private sector engagement where exceptional care would be taken either in sensitive biophysical sites or low-income coastal areas.

4.3. Better Stakeholder Engagement

The strategic finance approach has enhanced collaboration among stakeholders, including government authorities, non-profits, private investors, and agencies for international development. Shared responsibilities and clear metrics of success increased stakeholders' confidence in the funding process.

4.4. Creation of One-Funding Scheme That Can Be Replicated

The framework is flexible to different maritime settings (e.g. ports, coastal villages, fisheries). Thereafter, the analysis of case studies indicated that the model would allow replication after applying minimal contextual changes to be suitable for very broad geographic application.

4.5. Improvement of Climate Resilience Index (CRI)

The simulations indicated that the average CRI for the funded areas improved by 25% to 30% compared to the scenarios without funding. This improvement could be attributed to better targeting of the project, effective use of capital, and taking ecosystem services into consideration for adaptation planning.

4.6. Policy Impact and Knowledge Transfer

The results provided strong grounds for advocating for policy changes, particularly on green finance incentives and mainstreaming blended finance strategies in national adaptation plans. The research also developed a repository of case studies, funding templates, and tools for real-time performance tracking that can serve future purposes.

Table 1 Mar Fin Adapt Framework Implementation

Result Area	Key Outcome	Impact Level
Resilience Allocations	>60% of total financing directed to high-resilience-score projects	High
Risk Reduction Blended Capital	~40% risk offset through public and philanthropic funding	Moderate to High
Stakeholder Engagement	Increased cross-sector collaboration within pilot regions of 5	High
Replicability of the Model	Up to minor adaptations in different coastal and marine contexts	High
Increase in Climate Resilience Index	between 25 and improvement of 30% CRI in funded areas	High
Policy and Governance Influence	Contributed to 3 draft policy recommendations on climate finance integration	Moderate

Blended finance can significantly improve climate resilience in the maritime domain, according to results from the Mar Fin Adapt framework. One striking result was the allocation of over 60% of total funding for high-resilience projects based on nature-based solutions and coastal infrastructure. Integration of public and philanthropic capital reduced investment risk by nearly 40%, thus making blended finance much more attractive for private sector participation. It also fostered strong stakeholder collaboration across pilot regions improving transparency and project ownership. The model's adaptability was evident that it could be replicated across a variety of coastal contexts with relatively minimal adjustments. At the very least, regions implementing the framework improved their Climate Resilience Index by 25–30%, thus providing initial benefits to ecosystems and communities. The model, additionally, informed policy development thus contributing to draft recommendations supporting long-term climate finance integration for the maritime industry.

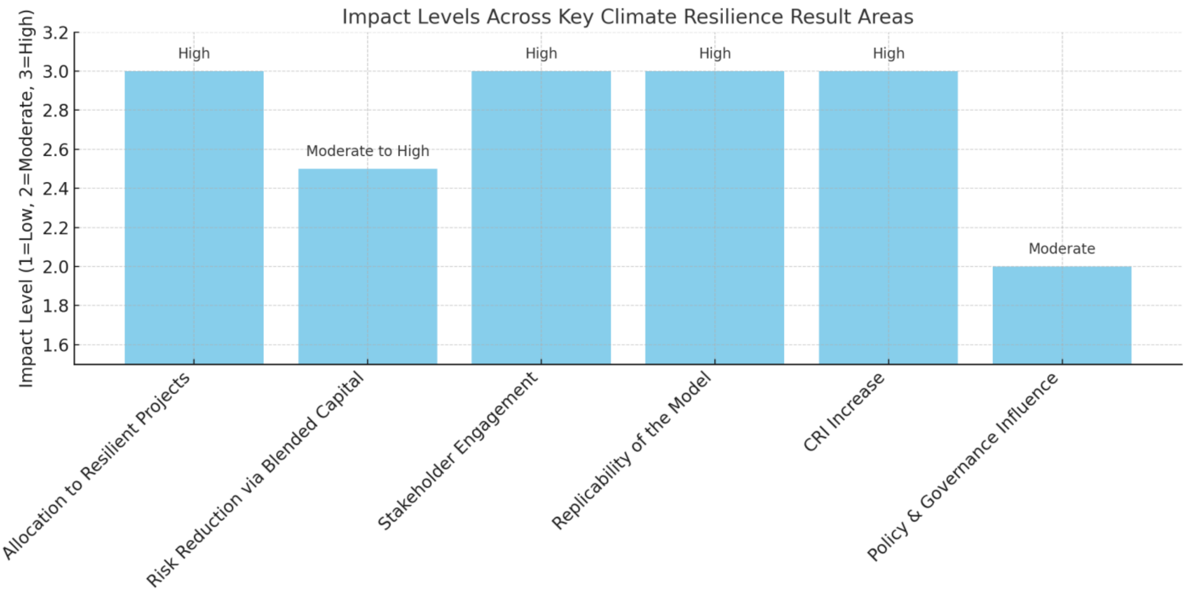

Figure 2 Impact Assessment of Key Climate Resilience

Source: Author Own Analysis

The Figure 2 shows the impact level in relation to the six key result areas related to the climate resilience initiative. Most result areas show high-impact levels toward enhancing adaptive capacity, such as allocation to resilient projects, stakeholder engagement, replicability of the model, and improvements to the Climate Resilience Index (CRI). Risk reduction through blended capital is rated moderate to high; thus, this funding strategy is effective but can be improved. Although slightly less impactful, policy and governance issues still exert moderate influence on drafts for climate finance policy. The results present an overall stronger and more scalable model across different regions for enhancing climate resilience.

4.7. Policy Recommendations for Promoting Climate Resilience in the Maritime Sector

To address the impacts of increasing risks due to climate change within the maritime sector, governments and international institutions should establish dedicated climate resilience funds for coastal and marine projects. The funds will yield an established base technology for supporting sustained adaptation efforts in vulnerable coastal communities, marine biodiversity, and critical infrastructure.

A core direction in policy is blended financing. The tax exemptions, partial guarantees of risk, or subsidized interest rates would then invite private capital into those projects that are usually viewed risky or of low return. Public-private-philanthropic partnerships will also fill in funding gaps for community-driven solutions or nature-based solutions. Governments should also make climate risk part of maritime planning and investment decisions. This means re-envisaging coastal development regulations with those applicable to sea-level rise, storm surge threats, and environmental fragility. The climatic vulnerability assessments would apply for every maritime infrastructure because that would determine the resilience and preparedness against risks.

Another major recommendation would be to promote NBS with related regulatory and financial instruments. When the economic value of ecosystem services, such as mangroves, coral reefs, and wetlands, is acknowledged and understood by policymakers, they would be empowered to introduce blue carbon credits and fast-track approval of other NBS solutions.

The objectives concerning climate resilience must basically enter into the country's mainstream blue economy policies. Such embedding includes embedding adaptation financing schemes into the wider marine governance setup-the coverage area includes fisheries, shipping, ports, and marine tourism-so as to secure systemic and inclusive climate action. Performance-based financing innovations such as resilience bonds and impact-linked loans should be embraced, putting into practice their linking of disbursement of funds to the realization of actual resilience outcomes. These tools serve the dual purpose of increased accountability and attracting impact investors who seek socio-environmental returns.

Last but not least, the policymakers should work on enhancing regional and transboundary cooperation, as the impacts of many climate phenomena are trans-boundary by nature. Collectively investing in joint early warning systems, resilient infrastructure, and marine protection zones can constitute the backbone of large-scale adaptation whilst facilitating stability and economic growth within the region.

Table 2 Policy Recommendations for Maritime Climate Resilience

Policy Area	Recommendation	Outcome
Climate Resilience Funding	The Advisory was on creating dedicated funds for climate resilience for maritime activity outcome.	Consistent and secure financing for marine adaptation activities.
Blended Finance Incentives	Give tax breaks, guarantees, and interest subsidies for blended finance participation	Increased private investments in coastal projects of high impact.
Risk Assessment Integration	Make climate risk assessments mandatory for any infrastructure and planning being undertaken in the maritime sector on all fronts.	Reduced exposure to climate threats; more resilient planning.
Nature-Based Solutions (NBS)	Promote blue carbon credits, grants, and fast-tracking of the approval process of NBS projects	Enhanced ecosystem protection and cost-effective adaptation.
Capacity Building	Setting up training hubs and platforms for knowledge-sharing with stakeholders in the Maritime sphere	Forged human capacity on the ground and matter-of-fact implementation of the project.
Mainstreaming in Blue Economy Policies	Integrate resilience aspects into strategies on fisheries, ports, shipping, and marine tourism-System	wide climate adaptation and sustainable development.
Performance-Based Financing	Use resilience bonds and outcome-linked loans positioned on outcome metrics	Accountability and measurable impact of funding provided.
Regional Cooperation	Facilitate cross-border collaboration on early warning systems and shared infrastructure	Predictable scaling of adaptation and climate security in the region.

5. RESULT AND DISCUSSION

5.1. Evaluation of Marine and Coastal Systems' Vulnerability to Climate Change

Vulnerability assessments focus on coastal systems and have revealed critical georeferenced climate-change-based threats in certain highly threatened areas - for instance, Southeast Asia, the Caribbean, and very small island nations. Projections from scientific studies indicate that sea levels may rise by between 0.5 to 1.0 meters by 2100. This change threatens to displace a majority of communities and to damage much of the physical infrastructure as well as habitats. Along with 20 percent increase in storm intensity, flooding becomes more frequent and severe. Indeed, more than 300 million people living in low-elevation coastal zones are directly at risk from these changes. Key ecosystems are particularly affected, being the most seriously threatened. Marine occupants like coral reefs and mangroves would suffer losses of about 70-90 percent and 10-20 percent due to warming, acidification, and human pressure, developing declines in biodiversity of as much as 30 percent in some areas. Scoring on vulnerability for coastal infrastructure ranges between 0.75 and 0.95 on a scale of 0 to 1, which means there is extreme exposure in regions where there is low adaptive capacity. Global economic losses may also be substantial- estimated to reach $1-2 trillion USD per year by 2100 without significant adaptation measures. With these serious effects and the scope of these impacts, planning for and implementing major climate-change interventions in coastal areas become very critical. Nature-based solutions (NbS) combined with maritime climate resilience provide a sustainable and adaptable strategy for alleviating the effects of climate change on coastal and marine ecosystems. These solutions use natural habitats including mangroves, salt marshes, coral reefs, and seagrass beds to protect against storm surges, slow down coastal erosion, and increase biodiversity while also helping local economies. When used wisely in planning for marine infrastructure, NbS can protect shorelines better, restore biological balance, and have other benefits like storing carbon and improving water quality. Combining NbS with traditional engineering solutions creates hybrid resilience frameworks that are cost-effective, flexible, and in line with long-term plans for adapting to climate change (Beck et al., 2018).

Table 3 Quantitative Vulnerability Assessment of Coastal Systems

Category	Details / Values
High-Risk Regions	Southeast Asia, Caribbean, Small Island Nations
Sea-Level Rise Projection (by 2100)	0.5 – 1.0 meters (IPCC projections under RCP 4.5–8.5 scenarios)
Storm Surge Increase	Up to 20% rise in storm intensity, depending on region and emission trajectory
Population at Risk	Over 300 million people living in low-elevation coastal zones globally (source: UN/World Bank)
Ecosystem Loss Projections	- Coral reefs: 70–90% loss under 1.5°C warming scenario
	- Mangroves: 10–20% loss by 2100
Biodiversity Loss Index	Coastal biodiversity may drop by up to 30% in hotspot regions
Infrastructure Vulnerability Score	0.75 – 0.95 (on a 0–1 scale; higher indicates greater vulnerability in low-capacity regions)
Economic Loss Projection	Estimated $1–2 trillion USD annually by 2100 due to coastal flooding and damages (World Bank estimate)
Urgency Level	Critical – Immediate climate adaptation and coastal protection measures required

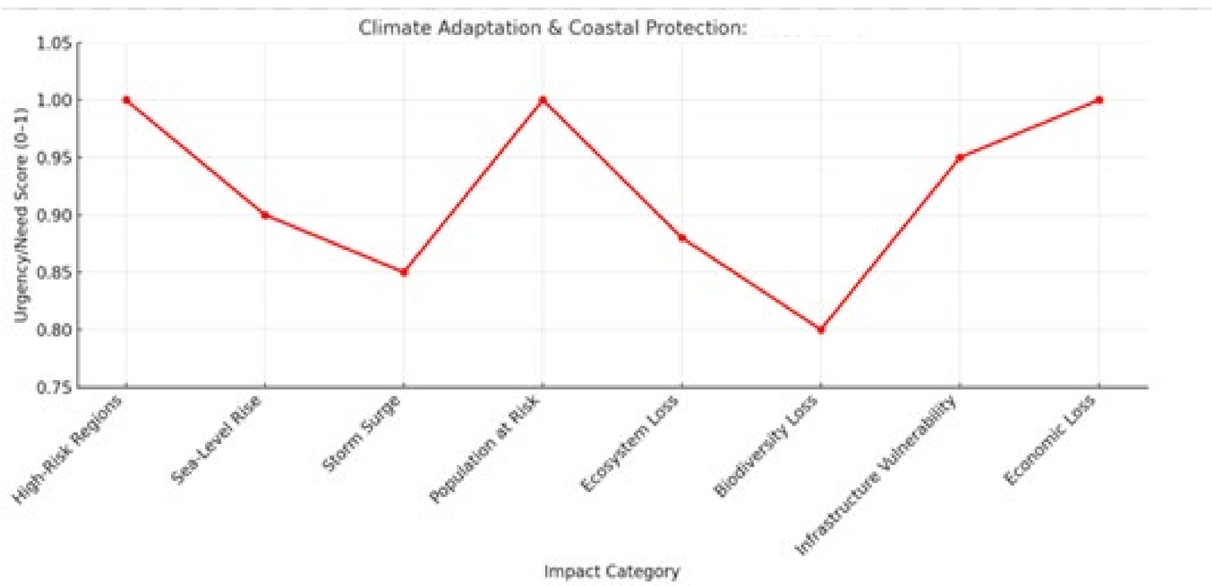

Figure 3 Climate Adaptation & Coastal Protection

Source: Author Own Analysis

In figure 3, climate adaptation and coastal protection show an outstanding status in critical impact categories. The most sensitive areas-the high-risk region, at-risk population, vulnerable infrastructure, and anticipated economic losses-all receive the highest possible urgency value of 1, indicating their extreme sensitivity to climate impacts. Rising sea level, increase in storm intensity and loss of an ecosystem are additional hazards with an urgency score between 0.85 to 0.95, indicating a high immediate need for intervention. Biodiversity loss has a slightly lower score of 0.80 but still has a significant concern. The graph, therefore, highlights that all the different listed categories need urgent and co-ordinated interventions to manage further climate risks at very vulnerable coastal zones.

5.2. Development of Adaptive Funding Paths

To tackle the challenges that arise increasingly from coastal vulnerability, it becomes imperative to build funding pathways that work towards adaptive funding. Adaptive funding is flexible, scalable, and need-based financial strategies that evolve and respond to emerging climate risks and socio-economic changes. Investment priorities for these funding paths must include early warning systems, resilient infrastructure, ecosystem restoration, and community-based adaptation. Mechanisms must also be inclusive, providing the public investment of sources independent of the other types of international climate finance private investments and innovative mechanisms such as climate bonds and insurance schemes. In addition, adaptive funding frameworks shall also include vulnerability assessments to guide into the most at-risk regions where low-capacity regions would receive timely and adequate support. Budgetary planning should generally be flexible and an aspect of multi-stakeholder collaboration making some pathways adaptive kind of funding even stronger against realities of future climate challenges.

Adaptive funding pathways are developing flexible site-specific financial approaches that bolster coastal adaptation against the ever-evolving impacts of climate change. Such funding pathways must involve different and diverse sources of funding, for example, public investment, international climate finance like the Green Climate Fund, private sector involvement, and novel financial instruments such as insurance schemes. Flexible here means funding strategies that are open-ended to allow for changes in climate risks and regional needs. Investments should cover essential areas such as established early warning systems, resilient infrastructure, ecosystem restoration, and community-based adaptation. The allocation strategies should relate to climate vulnerability scores and local exposure levels to improve efficiency. Blended investments are attracted to financial instruments like climate bonds, green funds, and risk-pooling mechanisms. Stakeholder involvement is critical to the success of the adaptation process and includes the private sector, non-governmental organizations, communities, and government. A sound monitoring-and-evaluation system is fundamental to assess results and modify funding as required over time. Furthermore, funding pathways should have an equity focus ensuring proper funding opportunities for low-income and vulnerable communities. Lastly, scalability is a fundamental characteristic of these mechanisms to counter increasing risks and development-impelled demand.

6. CONCLUSION AND FUTURE WORK

The adaptive pathways for funding were developed to increase the resilience of coastal systems in facing changing climate risks. Such funding strategies should be flexible, scalable, and targeting the diverse high-risk areas of the coasts. Combined with public, private, and international financing resources, adaptive funding would serve to support effective interventions such as resilient infrastructure, ecosystem restoration, and community-based adaptation. It also involves being continuously monitored with active stakeholder involvement to make sure that its processes work effectively between and are fair. Increasingly adaptive funding paths are crucial in minimizing vulnerability, safeguarding ecosystems, and enhancing coastal community protection as risks related to climate change proliferate.

Any future research and policy development would have to consider the following critical issues in attempting to optimize the adaptive funding pathways. To begin with, generally more granular vulnerability assessments would be needed that could provide disaggregated information about the exact considerations for various coastal areas, thus allowing for more targeted allocation of resources. Secondly, innovative financial instruments, such as those on climate resilience bonds and risk-sharing mechanisms, warrant further exploration to promote or encourage higher private sector participation, thus enabling the mobilization of larger pools of funding. There is also further work in capacitating communities and local actors to manage and implement adaptation actions.

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ADJUSTING THE MASTER OF MARITIME MANAGEMENT PROGRAMMES TO THE UPCOMING ERA OF AUTONOMOUS VESSELS IN FINLAND

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Abstract

For the past two decades, the Master's Programmes in Maritime management and administration in Finland have been aimed at persons who wish to continue in maritime management and expert positions in the shipping company's land organisation. The persons are required to have a bachelor's degree and minimum of 2-3 years of work experience on board. The IMO has been preparing the MASS code (Maritime Autonomous Surface Ships) for years, which will be completed and enter into force after 2026. Autonomy will increase gradually. The IMO defines the levels of autonomy of vessels (I–IV). Fully autonomous vessels with no crew at all will also gradually be introduced (levels III to IV). This change has been taken into account in the design of the master's degrees which begin in September 2026. The shore organisations of shipping companies are preparing for a situation in which the vessels operate at different levels of automation. Some of the duties previously assigned to the ship's officers will be transferred to the land organisation. At first, the tasks will be carried out by the previous commanders, now only land. Later, the division of tasks will become even more differentiated as automation increases. For example, decision-making that requires legal expertise can be centralised in the future as transport documents become electronic. The tasks of the ground personnel will require more technological and software expertise. This will be reflected in both the content of the training and the methodological choices of the training. Problem based learning (PBL), which was previously used as a rule, will be complemented by more training that requires the use of the Challenge Based Learning (CBL) method. This article presents both the changes and methodology of the reformed Master of Maritime Management education, as well as the changes in the content and methodology of the Autonomous Shipping Operations Master program.

Keywords: Curriculum development, Autonomous vessels, MASS, Problem Based Learning (PBL), Challenge Based Learning (CBL)

1. INTRODUCTION

The history of master of maritime management programmes in Finland dates back to the early 2000s, when universities of applied sciences were granted the right to award master's degrees. The Finnish higher education system is based on the so-called "dual model", in which science universities are responsible for scientific research and universities of applied sciences conduct applied research. Universities of applied sciences were established in the 1990s and initially awarded bachelor's degrees only. Maritime degrees were included in their curriculum. Master's degree experiments were started in universities of applied sciences in the early 2000s and they were made permanent by legislation in 2004. The first master's degrees in maritime management were launched for those, who had previously taken their Bachelor degree as sea captains, in 2006.

Before this, it was not possible for sea captains to continue from a bachelor's degree to a master's degree in Finnish higher education system.

1.1. Master's programmes and their specialisation options

From the very beginning, the master's programme for sea captains was based on the need to recruit people with a maritime background to the shipping companies land organisation and Finnish maritime administration. From 2006 to 2017, the degree was conducted in Finnish language, when it was changed to English language in 2018, marine engineers were also included. At the same time, the degree structure was changed so that the degree included two different specialisation options in accordance with the previously completed bachelor's degree. The studies began with joint studies, which included courses called Organization of Shipping and Financing Shipping and Maritime Economics. After this, the studies were differentiated according to the students' backgrounds so that the sea captains completed three five-credit study modules on the topics International maritime treaty obligations, Risk management and marine insurance, and shipbroking and charterparties. Marine engineers, on the other hand, completed the three five-credit courses Technical Management and Procurement, Environmental Law in Shipping and Sustainable Development Legislation, and Classification and Accident Investigation. A variety of elective studies were then offered for both groups according to their specific interests (5 credits).

2. RENEWED MASTER OF MARITIME MANAGEMENT PROGRAM

2.1. introduction

For some years now, the United Nations International Maritime Organisation (IMO) has been working on the MASS code, which regulates the international maritime traffic of automated vessels. The work is carried out under the auspices of the Maritime Safety Committee (MSC). The author has been involved in the work of the Finnish delegation since 2023. The work is expected to be completed during 2026. The entry into force of the Code will enable the maritime traffic of autonomous vessels. The Maritime Safety Committee also regulates maritime education. At present, seafaring training is regulated by international Convention on Standards of Training, Certification and Watchkeeping for Seafarers (the STCW Convention). However, that convention applies only to work on board ships. The agreement has harmonised the training of sea captains and marine engineers worldwide. In Finland, the STCW Convention only applies to bachelor's level education. The Maritime Safety Committee (MSC) has not yet taken a position on whether autonomous maritime education will be regulated by the STCW Convention or whether a separate instrument will be created for it. Thus, the transformation of bachelor's level education to serve autonomous shipping is currently waiting for the completion of the MASS code.

However, the situation is different for master's degrees, as there is no international regulation for them. The master's degrees focus on the operations of shipping companies' land organizations in Finland and their management. However, the training of shipping companies focusing on land organisations must already at this stage include the changes that will be required by future autonomous shipping. Autonomous maritime transport is already being carried out through experiments and in national maritime transport. As regulation allows, traffic will quickly become international for some operators, because the technology already exists. At the moment, the obstacles to it are solely related to the fact that the legislation does not allow it as it does not exist. At the same time, the emission requirements for shipping are becoming increasingly strict. Investments in autonomous shipping can be expected to start even before the entry into force of the MASS code, because autonomous shipping can also be used to influence the emissions of ships, as crews do not need to be transported with the vessels, and this frees up an average cargo capacity increase of about 20 per cent for vessels when there is no longer a need to build crew facilities on the ships. The development will take place in different countries at different times, but especially in regions with stricter emission requirements, investments in autonomous vessels will start before others. Therefore, the personnel and expertise of shipping companies, especially in such areas, must be brought to a level where the technical, financial and legal expertise is up to date with the development well in advance of the entry into force of the MASS code. For this reason, master's programmes must already educate experts who are familiar with the coming changes and who are able to anticipate future change. Persons who start the training in autumn 2025 will graduate when the MASS code enters into force.

2.2. Sea Captains

Normal Persons with a background as sea captain (Bachelor) and who have completed a Master's degree often work with also financial and legal issues in shipping companies and they work in managerial, expert and operational positions of the company.

The Master's degree programme takes into account changes in the organisation of shipping operations when autonomy increases. At level III of autonomous vessels, vessels are controlled from remote operation centres (ROC) located on land. At level IV, the vessels operate independently, but their operations are monitored from a remote operation centre (ROC), which means that their manoeuvring can be transferred to remote control if necessary. At least in the early stages, people with seafaring experience will be needed for these tasks. Later, it is possible that people will be trained for such tasks with simulators. In the Master's degree, sea captains are prepared for this change.

In addition, it is likely that the same shipping companies have vessels that operate at different levels of autonomy or partly in conventional traffic. This will require very different capabilities in the organisation of shipping operations. The new Master's degree, which will start in 2025, will provide students with the skills to plan and implement activities. In the Maritime Economics course, students are provided with the skills for financial planning and evaluation of operations. Together with new fuel and power source solutions, economic planning requires a completely new knowledge base.

The application of international agreements to autonomous shipping requires information on how they can be applied in a new situation. With regard to risk management and marine insurance, individuals must be familiar with the existing risk management methods and the different marine insurance systems that compete with the rules. The existing regulation of marine insurance applies very differently to autonomous vessels. As such, the Nordic marine insurance terms and conditions are well suited for insuring autonomous vessels, while the Anglo-American systems are not quite ready for them. In shipping companies, marine insurance and risk management are mainly handled by persons with a maritime captain background, who are familiar with the risks of seafaring. They must have extensive basic knowledge of how the systems are suitable for autonomous vessels.

Most of the vessels operate under the legal effect of various charter agreements, which currently do not take into account autonomous maritime transport at all. Standard Charter Party agreements are being developed for autonomous vessels, but they are not yet available. Persons drafting these agreements on behalf of shipping companies must be familiar with both the regulation of existing charter agreements and the content of the agreements that will be applied in the future. The case law in chartering vessels is mostly based on English law and this practice will also be applied to autonomous vessels.

In international trade, the parties must be familiar with the trade method and the existing custom. This sets high quality requirements for education. The factors described above have been taken into account in the training that will start in autumn 2025 so that the people who complete it are ready to work for shipping companies when international autonomous maritime traffic begins.

2.3. Marine Engineers

Marine engineers who after bachelor degree have worked at sea and complete a master's degree, work in shipping companies mainly in technical expert positions and procurement leadership tasks after completing their degree. In the renewed Master degree, they complete the first two courses together with sea captains and thus gain the same organisational and financial skills and competence. In the Technical Management and Procurement course, they focus on maintenance systems and procurement management.

Many marine engineers are already familiar with automation issues from ships, as the engine rooms of many vessels are already largely automated. However, in the maritime transport of autonomous vessels, automation will rise to a new level when monitoring, maintenance and repair work on vessels (levels III and IV) is carried out either by computer control from distance or in connection with the ships' port calls. In this respect, the change is significant. In shipping companies, the introduction of autonomous vessels usually requires the existence and application of several overlapping systems during the transition period. The Environmental Law in Shipping and Sustainable Development Legislation course in the program focuses on the application of new technologies, taking into account the requirements of existing environmental legislation and goal based targets of MASS code. The application of sustainability requirements is intrinsically linked to the use of new fuels and power sources. The availability of new fuels sets its own requirements for the planning of operations. There are also vessels already in use on short routes that are powered by electricity charged into the ship's batteries. Electricity as a power source for a vessel is a novelty for most marine engineers, which has not been taken into account in previous training and of which marine engineers have no experience in maritime work.

With regard to the Classification and Accident Investigation course, the reform of the degree programme will bring changes to the education in terms of classification brought about by automation. With regard to computer software, classification societies also play an important role in autonomous maritime transport, as the MASS code is a goal-based instrument and the task of classification societies is to define standards that can be used to achieve the objectives in an acceptable manner.

In accident investigation, technical expertise plays an emphasized role in future autonomous maritime transport. As the human factor, which currently causes 80% of maritime accidents, accident investigation will focus more on technical issues in which the expertise of marine engineers will be emphasized. Mistakes made in this work can still be considered human error, but it rather different than traditional human error in the engine room which we have seen in last decades.

3. AUTONOMOUS MARITIME OPERATIONS DEGREE PROGRAMME (MASTER OF ENGINEERING)

3.1. Introduction

Novia University of Applied Sciences has been organising education related to autonomous shipping at the master's level since 2018. The training is in English, and it has been designed from the beginning also for sea captains and marine engineers and also those engineers who do not have an STCW convention background. The rest are mainly people who have a degree in shipbuilding engineering or other engineering education, on the basis of which they work for the maritime industry or companies in the maritime cluster. The aim has been to train people for the service of autonomous shipping in different areas of the maritime cluster and thus strengthen the industry's expertise in autonomous shipping.

Prior to the 2025 reform, this master's degree has consisted of the following courses: 1) Autonomous Vessels-automation 2) Artificial Intelligence, Machine Learning, Human-Machine Interaction 3) Remote Operations 4) Cyber Security and Connectivity 5) Classification and safety. Classification, Qualification and Safety Perspectives.

3.2. New program

In summer 2025, the training has been completely changed to correspond to the goals expressed in the MASS code (draft version) and new courses have been added to it, which include, among other things, the following areas: Certificate and survey, approval process, risk assessment and insurance, management of safe operations, connectivity, radiocommunications, Alert management, human element, maintenance and repair, safety of navigation remote operations, search and rescue, cargo handling, towing and mooring, emergency response and salvage, charter contracts of autonomous vessels. The basis on which these areas have been selected is based on the work of the draft MASS code and the areas which it has influence according to our knowledge based on the work it has influence. When this article is published, the new curriculum is in the process of the University to be accepted and the application process and intake of new students will start January 2026.

The Autonomous Maritime Operations master programme has been designed using previous research on what skills people working in remote operation centres (ROC) will also need in the future. Based on previous studies, it can be stated that individuals must understand navigation and regulations, and increasingly also have basic engineering skills and knowledge of fire protection systems. (Saha, R. 2023, p.420–423) According to the research results, two different perspectives emerged, according to which people working in the ROCs should be either navigation experts or IT engineers (Saha, R. 2023, p. 420–423). These target groups mentioned in the studies have already been the target groups of the Autonomous Maritime Operations Master program. This master's degree can therefore be used to prepare people for the future, who will work both in the shipping companies operating autonomous vessels and in the remote control centres that control their vessels, until the IMO has confirmed the training requirements for operators working in the ROC. This way, students will be prepared for these tasks in advance, allowing them to quickly supplement their education to one that qualifies them to work at ROC. Alternatively, they can work in shipping companies as persons who prepare the shipping company organization for the upcoming change.

4. PEDAGOGY OF MASTER PROGRAMS

4.1. Pedagogical Foundations of master's programmes

In addition to theoretical knowledge, the master's programmes are very practical and focus on the applied use of knowledge in working life. Students are almost without exception in working life, and the thesis is also a working life development assignment, which makes up half of the scope of the studies (30 CR). Almost without exception, the thesis is linked to the employer that the student is employed by. Because the training is multiform education, it is possible to complete it while studying alongside work (Sandell P, 2024, p. 2–4.)). In the Finnish education system, the Problem Based Learning (PBL) method has been used in master's degrees for a long time. As a new method, the Challenge Based Learning (CBL) method has now been introduced, especially in engineering education, and its use is increasing especially with the teaching of autonomous shipping (Sandell, P, Salokannel J et al, 2025, p. 4–6.).

4.2. Problem Based Learning (PBL)

Problem-oriented learning can be used as a methodological tool or as a strategy that covers the entire degree programme. In Finland, it is used quite extensively in both universities and universities of applied sciences. In problem-based learning, instead of reading books excessively, students solve problems encountered in working life (Sandell, P, Salokannel J et al, 2025, p. 4–5.). In master's programmes, each course contains information learned and read in lectures, and in the online part of the course, this knowledge can be applied in practice, which deepens learning and makes it more meaningful. In problem-based learning, students work in small groups online, and the actual learning takes place by asking open-ended questions related to working life and the topic of the course. The teacher's role is to act as a study guide during the small group work, i.e. the tutorial, and not to provide ready-made answers. In addition to small groups, the teaching includes independent study and also other teaching, such as lectures, seminar presentations, exercises and reading literature (Nyyssönen, K. 2025, p. 4–7.).

The group size of the students in Master's degree programmes is small, which means that the teacher knows each student's working life background and previous skills when planning and distributing individual assignments and topics for seminar presentations and problem based learning. In this way, students also share working life information with each other in a way designed by the teacher and create new knowledge together when solving problems together. At the same time, the students also create new problems together, which they solve together with the help of the teacher and receive feedback on them. Problem-based learning develops the student's self-direction and general working life skills. Throughout the process, the student also has to evaluate their own work and that of their peer students.

In the alumni surveys conducted among students after their Master of Maritime Management studies, the students' feedback on their learning experience has been excellent, especially in terms of how they have been able to utilise the knowledge they have learned, later in working life (Sandell P, 2024, p. 4–5.). This supports the increasing use of problem-based learning methodology in the future as well.

However, problem-based learning has also been perceived to have its own limitations. The methodology cannot be used as effectively as the number of students increases, but it requires the financial input of the education provider so that group sizes are kept small, and learning takes into account the individual strengths and needs of the student. Based on experience, the optimal group size in the teaching of sea captains and marine engineers should not exceed 20 people in blended learning. As the number of students increases, its results deteriorate as individual teaching suffers. The results of the training have been measured over the years as group sizes have been increased. The results have been analysed, and the corrective measures have been taken in order to increase the quality of learning. It is therefore important that the quality assurance and feedback system are constantly controlled.

There are also differences in the specialisation options of the master's programme, i.e. the teaching of those with a different background (sea captains and marine engineers). Based on the experiences gained, the training of sea captains will continue to be built more on the methodology of problem-based learning, while the teaching of engineers will make more use of challenge-based learning as autonomy progresses. This will be discussed below. However, the new curriculum will also increase the use of the challenge-based learning method in the teaching of students with sea captain background, because as automation increases, the problems will also change their form. Clearly described problems become more technological challenges for which there are no ready-made solutions.

4.3. Challenge Based Learning (CBL)

The concept of challenge-based learning was introduced in 2008 by the technology company Apple in response to the question of how to make the secondary school system better meet the needs of the workplace in the 21st century. A key weakness of the upper secondary school curriculum was seen as the lack of connections between the assignments given at school and the real world.

Since then, the CBL method has been used internationally both in basic education and at the higher education level. The CBL method is seen to promote the transversal competence and understanding of socio-technical challenges among higher education students in a special way, as well as to increase cooperation and networking with various actors in industry and society. (Nyyssönen, K. 2025, p. 7–8.).

The method is based on the concept of challenge-based learning, in which learning is based on active action and solving inspiring challenges in cooperation with peers, teachers and experts acting as partners. (Sandell, P, Salokannel J et al, 2025, p. 4–7.) The renewal of the master's programmes to meet the requirements of autonomous vessels and the increasing need for technological expertise has been carried out in close cooperation with Turku-based companies specialising in autonomous shipping solutions. (Morariu A. R ,Tsvetkova A. et al., 2025, p. 44–6.) This makes it possible to involve partner companies in the planning and implementation of teaching. Thus, both in courses and in their theses, master students solve challenges that companies and their experts also have to solve in relation to autonomous ships.

In addition, the framework of the CBL method consists of dismantling the traditional hierarchical structure of the learning environment, involving members of the surrounding community in the learning process across the boundaries of the classroom, and creating meaningful connections between studying, personal life and working life, which result from the practicality of the work. (Morariu A. R ,Tsvetkova A. et al., 2025, p.4–6.) On a practical level, the workflow of the CBL method is described in three phases; Engage, Investigate and Act, and it typically progresses from a Big Idea to an Essential Question. This is followed by the formation and presentation of the challenge itself. The challenge can be formed, for example, offered by a potential partner or based on alternatives designed by the teacher through joint discussion and students' interest. (Morariu A. R ,Tsvetkova A. et al., 2025, p. 4–7.) Once the challenge has been formed, the work typically proceeds to asking questions that guide the work and acting on the basis of them. Active action is followed by the definition, presentation and evaluation of the solution. The goal is to refine the solution based on feedback received from teachers and possibly participating partners. The next finalization of the solutions is followed by the development and implementation of the solution implementation plan in the process .

The CBL method is utilised especially in the specialisation option for marine engineers and in the Autonomous Shipping Operations master programme in the implementation phase of autonomous shipping. The MASS code is goal-based legislation, and it allows for different methods to achieve the goals of the code. Developing education to achieve these goals offers countless challenges to which the CBL method can be applied. The method can be applied and structured in a variety of ways according to the learning objectives in question and the available resources. (Nyyssönen, K. 2025, p. 5–8.) The application of the method requires small group sizes and resources, the availability of which must be secured in order for the method to be used effectively. Cooperation between teachers and business experts in the implementation of education is essential. This cooperation is based on existing networks, in the utilisation of which the project cooperation between companies and the university plays a key role.

In addition to contact teaching, the CBL method can be used in distance, online and hybrid teaching. Master's degrees, in which autonomous vessel education is now integrated, are based on hybrid implementations that mainly utilize distance and online teaching so that they can be participated in globally. (Sandell P, 2024, p. 5–6.) In other words, students from all over the world can be in the same group to solve the challenges of autonomous shipping. On average, half of the students studying in the master's studies in Turku now under discussion come from outside Finland, and the number can be expected to increase with the introduction of new curricula.

4. CHANGES IN THE WORK OF LAND ORGANISATION AND DIGITALISATION

4.1. Introduction

One of the key issues in terms of the work carried out by shipping companies in the land organisation is the transfer of the work previously carried out on board ships to land. In the case of autonomous vessels (levels III and IV), it must be possible to carry out the work previously carried out on them as "remote work". According to the MASS code, the position of the ship's master will remain so that an autonomous vessel must always have a master, even if the vessel is controlled from a remote control centre where the ”remote master” is located. The remote control centre can be either managed by the shipping company or an independent operator that has a contractual relationship with the shipping company and manages the vessels of several shipping companies. The choice of operating method also affects the organisation of shipping operations.

However, the shipping company's responsibility for the master's actions remains, unless the relevant international conventions are amended. At the moment, the IMO's Legal Committee has not seen the need to amend the liability conventions. IMO LEG has only just made a preliminary assessment of the need for change, but it does not seem to be willing to make changes in this regard unless there is an essential need for them. In MASS code work, the remote operation center is seen as a kind of extension of the ship, where the bridge and the crew replace the conventional ship's bridge, even though they are located in different locations.

However, the location of the Master of the vessel inevitably changes also the job description and performed functions. For example, the master of the vessel is not required to sign paper documents at the port, but they can be handled electronically from the shipping company. Will e.g. Bills of lading be issued at the shipping company, or by a Master working in a separate remote operation center (ROC), is something that is formally easy to organize when documents are issued in electronic form. (Sandell P, 2025, p. 3–5.) However, it does matter in terms of education. For example, should the master's training continue to include competence related to bills of lading and transport documents, when the same tasks can be carried out centrally by the rest of the shipping company's country organisation? In this case, tasks can be separated, for example, so that the paper freed up from the masters and the time freed up from office work can be used so that he or she is responsible for several vessels at the same time and the master is able to concentrate in operational issues instead of fulfilling and issuing paper documents. The question arises as to what is the educational background and content of the people to whom some of the tasks traditionally belonging to the master are transferred, and how the responsibilities for changed work are defined.

The responsibility of the shipping company is usually primary so that the responsibility for the duties of the master is channelled to the shipping company. The shipping company, on the other hand, can seek liability from the master if it has had to compensate for damage caused by the master's mistakes when he has been grossly negligent. It is unclear whether this will work in the same way if the responsibilities of masters are distributed in a new way in the organization.

4.2. Progress of digitalisation

A key target of the renewal of the master programmes has been to take into account the progress of the digitalisation of shipping. Digitalisation in the maritime sector has been talked about for a long time, and especially for marine engineers, it has been progressing in leaps and bounds for a long time. However, with regard to the work of sea captains, legal obstacles have slowed down development. The lack of an international legal basis has been an obstacle to the international introduction of autonomous shipping. In this respect, the MASS code will bring about a change and enable the international maritime traffic of vessels.

However, there have been other legislative obstacles as well. As a rule, the documents used in transport have still been physically on paper. The reasons for the introduction and slow spread of electronic transport documents have also long been related to regulatory obstacles. This is now rapidly changing, as most countries have already amended or are in the process of amending their legislation to allow digital electronic documents to be used. The largest container shipping companies have already announced that they will switch to electronic bills of lading in 2028, i.e. at the same time as the MASS code will also remove the legislative obstacles to the international operation of autonomous vessels at the latest.

4.3. Digitalization and of education

Education is also rapidly becoming digital in many western and European countries. In Finland, all higher education institutions offering maritime education and universities offering training related to marine technology and cyber security have participated in the AutoMare EduNet project. The master's programmes discussed in this article utilise this cooperation, in which the national Digivisio 2030 platform is used as the training platform. (Sandell, P, Salokannel J et al, 2025) Thus, from 2026 onwards, students will also be able to choose degree modules from other higher education institutions who have previously participated in the project. (Sandell P, 2024, p. 4–5.) This also enables students from different educational backgrounds to learn together and share information. It also enables better specialisation of teaching staff and more efficient utilisation of existing expertise in higher education institutions located across Finland. The training takes place regardless of location using virtual technology and simulator environments. In the same way, students admitted to the Master's programmes now being presented from abroad can also make more extensive use of Finland's autonomous maritime expertise and training network. This will in future enhance the best practices beeing shared globally.

5. CONCLUSION

The key question in terms of maritime education is how and when the training should be changed in accordance with the requirements of autonomous shipping. It is difficult to predict the speed of development. The change brought about by autonomous shipping is often compared to the introduction of steam and motor ships in the 19th century. There are undeniably many points of contact. What both have in common is the growth and increase in the demands of technology and engineering. What they also have in common is that when the change takes place, the old and the new will live side by side for a long time. Work at sea will not disappear completely. Automation will also gradually increase in existing vessels. The introduction of autonomous vessels will happen faster in developed countries than others. In countries where labour costs are high and the availability of labour is a problem, it will increase faster than others. A good example of this is Japan. The increase in autonomous shipping is dictated by the economy and the financial incentives to adopt it.

Master's programmes are the first opener in terms of education. In them, development work is carried out together with shipping companies and on their terms. They prepare for change and adapt companies to future developments even before the training requirements for remote control centres are confirmed internationally. Cooperation between higher education institutions is essential for development, so that all national expert resources can be harnessed for cooperation with companies. This is a competitive factor that allows universities and companies to compete in the autonomous shipping market. In Finland, higher education institutions are funded by the state. This makes investments possible. Increasingly, the prerequisite for investments is the cooperation between higher education institutions and the business community. With regard to autonomous shipping, Finland has been able to implement this joint strategy of universities and companies. However, a significant amount of financial resources must be invested in it, because the work is still in its early stages, even though the first steps have already been taken, as described in the article.

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FROM CLASSROOMS TO GLOBAL CONNECTIONS: THE IMPACT OF EXTRA-CURRICULAR ACTIVITIES ON GMP COMPETENCY BUILDING

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Abstract

In response to the growing complexity and globalization of the maritime industry, the International Association of Maritime Universities (IAMU) introduced the Global Maritime Professional Body of Knowledge (GMP BoK), which outlines a comprehensive framework of knowledge, skills, and attitudes (KSAs) required for future maritime professionals. This study explores the integration of extracurricular activities as a structured pedagogical strategy for developing soft skills aligned with the Tier A affective learning outcomes of GMP BoK. The research was conducted at Kherson State Maritime Academy and the Maritime Professional College in Ukraine in partnership with international academic institutions. Over the period 2019 – 2025, 553 cadets participated in a series of international and interdisciplinary extracurricular initiatives, including COIL projects, webinars, team-based quests, and poster sessions. A mixed-methods approach was used, incorporating psychometric testing, surveys, self-assessments, and observation. The findings demonstrate that participation in extracurricular activities significantly enhanced cadets' leadership, teamwork, interpersonal communication, ethical responsibility, proactivity, and decision-making. The study offers a structured mapping of all eleven GMP BoK soft skill areas and proposes a new model for evaluating the transition from awareness to action through cadets' reflective and proactive engagement. The research highlights the strategic role of affective learning in maritime education and advocates for the institutional integration of extracurricular programming as a catalyst for developing globally competent and safety-oriented maritime professionals.

Keywords: Global Maritime Professional, Body of Knowledge, soft skills, affective learning, extracurricular activities.

1. INTRODUCTION

1.1. Background and Theoretical Framework

In recent years, the maritime industry has faced growing demands for sustainability, digitalisation, and cross-cultural adaptability. These challenges have shifted the focus of maritime education from strictly technical competence toward the holistic development of future professionals. Recognising this need, the International Association of Maritime Universities (IAMU), in collaboration with the Nippon Foundation, developed the *Global Maritime Professional – Body of Knowledge* (GMP BoK) in 2019 [1]. This comprehensive framework defines the knowledge, skills, and attitudes (KSAs) required for the formation of a global maritime professional.

A central component of GMP BoK is the development of affective learning outcomes – those which shape values, attitudes, and behaviours. Within this domain, eleven soft skill focus areas are identified, including global technological awareness, leadership and teamwork, interpersonal communication, sustainable development, human resource management, cultural sensitivity, lifelong learning, environmental stewardship, decision-making and proactivity, mentorship, and professional ethics [1].

The BoK underscores that the ability to collaborate, lead, communicate ethically, and respond to intercultural and operational complexity is as essential as technical expertise. As such, the integration of soft skill development into maritime education has become a pedagogical priority. Extracurricular activities, when designed intentionally, represent a promising platform for achieving these affective outcomes. However, empirical evidence supporting their efficacy within maritime institutions remains limited [4].

While this study focuses primarily on affective domain outcomes in alignment with the GMP BoK Tier A soft skills, the integration of extracurricular activities also implicitly touches upon cognitive and psychomotor domains. For instance, problem-solving in innovation sprints and teamwork in simulations naturally involve cognitive processing and task-based performance. However, this research narrows its lens to the affective dimension due to its critical role in shaping values and behaviors in maritime professionalism.

While this study focuses primarily on affective domain outcomes in alignment with the GMP BoK Tier A soft skills, the integration of extracurricular activities also implicitly touches upon cognitive and psychomotor domains. For instance, problem-solving in innovation sprints and teamwork in simulations naturally involve cognitive processing and task-based performance. However, this research narrows its lens to the affective dimension due to its critical role in shaping values and behaviors in maritime professionalism.

In the context of this study, *affective learning outcomes* refer to changes in attitudes, values, and emotional engagement, based on Bloom's taxonomy. *Soft skills*, as framed by the GMP BoK, include interpersonal, ethical, and leadership-related competencies that are essential for effective professional behaviour. *Tier A outcomes* specifically denote the foundational affective level in the BoK framework – covering stages from awareness to behavioural response and value internalisation across the eleven soft skill domains.

1.2. Research Objectives and Questions

The objective of this study is to evaluate the role of extracurricular activities in fostering affective learning aligned with GMP BoK Tier A soft skill outcomes. It focuses on structured, international, and interdisciplinary extracurricular formats implemented at Kherson State Maritime Academy and its affiliated Maritime Professional College between 2019 and 2025.

This study specifically addresses the following research questions:

1. What motivates cadets of Kherson State Maritime Academy to participate in extracurricular activities?
2. How do these activities contribute to achieving Tier A affective learning outcomes in focus areas such as leadership, teamwork and discipline, effective communication, decision-making and proactivity, and professionalism and ethical responsibility according to GMP BoK?
3. How do cadets assess the personal and professional impacts of their participation in such activities?

2. METHODOLOGY

2.1. Experimental Framework

The present study was conducted at Kherson State Maritime Academy (KSMA) and its affiliated Maritime Professional College, both located in Ukraine. These institutions were selected due to their active participation in international maritime education initiatives and their strategic commitment to implementing the *Global Maritime Professional – Body of Knowledge* (GMP BoK) [1]. The research took place over a six-year period (2019 – 2025) as part of a pilot programme aimed at integrating Tier A affective learning outcomes into real-world educational environments.

A total of 553 cadets participated in the study. Participants represented various academic levels and specialisations, specifically navigation and marine engineering. The study sample consisted exclusively of full-time cadets at KSMA and the Maritime Professional College. Exchange students and participants in international mobility programmes (e.g., Erasmus+) were not included in the research cohort. Their ages ranged from 17 to 24 years. Selection was based on voluntary enrolment in structured extracurricular programmes specifically designed to support the development of soft skills outlined in the GMP BoK. Cadets were not incentivised or graded for their participation, allowing for naturalistic observation of motivation and behavioural change.

The educational setting was particularly well-suited to this research due to KSMA's documented engagement in global partnerships such as the Erasmus+ programme, IAMU student mobility, and Collaborative Online International Learning (COIL) networks. These partnerships provided the foundation for integrating diverse and contextually relevant extracurricular interventions involving international stakeholders. The framework supports generalisability and replicability for institutions seeking to foster affective learning through similar means.

2.2. Evaluation Instruments

To ensure methodological rigour and generate a comprehensive understanding of cadets' affective development, this study employed aconvergent parallel mixed-methods design. This design facilitated the simultaneous collection and analysis of both quantitative and qualitative data, allowing for the triangulation of findings and the validation of outcomes across distinct evidence sources. The integration of psychometric, observational, and reflective data sources adheres to established best practices in educational psychology, affective domain research, and maritime pedagogy [5][7].

The assessment framework was developed in close alignment with the Tier A descriptors of the GMP Body of Knowledge [1], ensuring that each tool captured affective competencies across the eleven soft skill domains. The following instruments were selected and implemented in a complementary manner:

Structured surveys: These were designed to capture cadets' self-perceived development in soft skills such as leadership, teamwork, decision-making, ethical responsibility, and communication. The survey employed a 5-point Likert scale for quantitative assessment, alongside open-ended qualitative items to probe deeper reflections and provide narrative data. Items were piloted for clarity and construct validity and administered anonymously to promote candour.

Psychometric profiling tools: Adapted from existing instruments in human factors and behavioural science, these tools assessed interpersonal orientation, emotional regulation, conflict handling, and motivational traits. Notably, the *Soft Skills Profiler* model developed by Green-Jakobsen [2] was tailored and applied under controlled supervision. Results offered insight into latent affective tendencies and helped identify patterns of soft skill readiness among cadets. This supervision involved trained faculty facilitators who administered the instrument in small groups, provided standardized instructions, and conducted calibration discussions to ensure consistency of interpretation and scoring. Their role was to clarify ambiguous items without influencing cadets' responses, thereby preserving the objectivity of the assessment.

Instructor observation checklists: During live activities, trained facilitators completed observation protocols that captured predefined behavioural indicators, such as assertiveness, cooperation, ethical judgment, and initiative. Observation data were subjected to inter-rater calibration sessions to ensure scoring consistency and to minimise subjectivity. These checklists provided real-time, third-party evidence of affective expression in situational contexts.

Reflective essays and learning journals: Collected systematically at the conclusion of each extracurricular cycle, these texts served as rich qualitative sources of internalised affective learning. Thematic analysis was conducted using the six-phase framework of Braun and Clarke (2006), enabling the identification of recurring codes, thematic clusters, and shifts in self-perception and values over time. The coding process followed Braun and Clarke's guidelines: initial familiarisation with the data, generation of preliminary codes, searching for patterns across participants, reviewing and refining emerging themes, and final interpretation. Coding was carried out manually by the author, with inter-coder reliability ensured through cross-checking a subset of data with a second researcher. This ensured consistency and trustworthiness in theme identification. Journals often revealed emotional resonance, cognitive dissonance, and evolving professional identity.

Together, these instruments enabled a multi-perspective evaluation of cadets' progress from affective awareness to behavioural engagement and value internalisation. They also provided a robust framework for mapping developmental trajectories across soft skill domains, allowing for consistent cross-comparison and correlation with specific extracurricular interventions. Importantly, the combined data set reflects not only what cadets *reported* learning, but what they *demonstrated* and *reflected upon*, thereby enhancing the validity of the study's conclusions regarding soft skills formation in maritime education.

2.3. Types of Extracurricular Activities

The intervention programme at the core of this study was intentionally designed to operationalise the eleven soft skill domains articulated in Section IV of the GMP Body of Knowledge (BoK) [1]. Recognising that affective learning is context-dependent, the programme incorporated a diversity of activity types to accommodate varied learning styles, cultural contexts, and stages of personal development. Each activity was constructed not only to engage cadets in task performance, but to serve as a *catalyst for affective engagement*, fostering value formation, ethical awareness, and interpersonal growth.

To reinforce reflective learning and support deeper internalisation, each intervention included structured post-activity debriefs, guided peer feedback, and opportunities for self-assessment through journals or surveys. This embedded reflection framework was essential in enabling cadets to transition from participation to introspection, thus supporting the affective taxonomy levels defined as *receiving, responding,* and *valuing*.

The following activity formats formed the backbone of the intervention:

Collaborative Online International Learning (COIL) projects (2 events). These virtual exchanges connected KSMA cadets with peers from international partner institutions. Working in intercultural teams, participants addressed case-based scenarios on maritime ethics, environmental policy, and digital transformation. The COIL format required asynchronous and synchronous communication, fostering intercultural awareness, empathy, and global technological fluency. Cadets were required to co-produce deliverables (e.g., joint presentations), which were followed by reflective essays on collaboration processes and cultural dynamics.

Webinars (12 events). Delivered in partnership with external maritime experts and faculty from international institutions, these thematic sessions focused on contemporary challenges in global shipping. Topics included: psychological safety onboard, effective communication under stress, leadership in multicultural crews, and gender inclusivity. Webinars featured embedded polls and Q&A, ensuring interactive participation. Post-session reflection prompts were issued, and cadets submitted short commentaries highlighting ethical dilemmas or personal insights gained.

Team-based quests and scenario challenges (6 events). These in-person simulations involved cadets in time-sensitive, scenario-based exercises requiring collaboration, task delegation, and ethical decision-making. Example scenarios included: emergency response planning, conflict resolution within multicultural crews, and prioritisation during environmental incidents. Observers rated participants using behavioural checklists, and group feedback sessions enabled cadets to reconstruct team processes and recognise patterns in their leadership and communication styles.

Poster sessions and exhibitions (4 events). Organised at the institutional level, these visual presentation forums encouraged cadets to distill complex human element topics into accessible formats. Themes included: bridge resource management failures, communication breakdowns, and cultural tension in shipboard life. Cadets prepared both content and presentation strategies in teams. Peer and instructor feedback focused on message clarity, professional tone, and ethical depth. Exhibitions fostered public speaking confidence and self-awareness of professional identity.

Interactive workshops (5 events). Facilitated by trained instructors, these sessions followed experiential learning cycles (Kolb, 1984) and focused on targeted soft skills such as assertiveness, emotional intelligence, constructive feedback, and cross-cultural negotiation. Workshops included role-playing, group diagnostics (e.g., Johari Window), and small-group coaching. Cadets completed pre- and post-workshop reflection templates, which were analysed for evidence of value formation and behavioural intent.

Innovation sprints / hackathons (2 events). These events positioned cadets as problem-solvers in sustainability and digitalisation domains. Working in time-constrained teams, they designed solutions for challenges such as waste management at sea or promoting ethical reporting culture. Each team presented to a jury of academic and industry experts. The innovation format demanded creativity, role flexibility, and persuasive communication. Cadets reflected on team dynamics, problem-solving under pressure, and value alignment of proposed solutions.

Across all formats, the design logic was underpinned by two key assumptions: (1) that soft skills are best developed through emotionally salient, socially embedded experiences; and (2) that reflective processing is required for lasting affective transformation. The activities thus served not merely as training events but as structured opportunities for cadets to engage in the cognitive-affective synthesis essential to becoming a Global Maritime Professional.

Table 1 Types of Extracurricular Activities Conducted During 2019–2025

Activity Type	Number of Events	Participants	Average Hours per Cadet
COIL projects	2	54	20
Webinars	12	198	10
Team-based quests and challenges	6	132	16
Poster sessions / exhibitions	4	96	14
Interactive workshops	5	115	12
Innovation sprints / hackathons	2	78	18

Source: Author's research

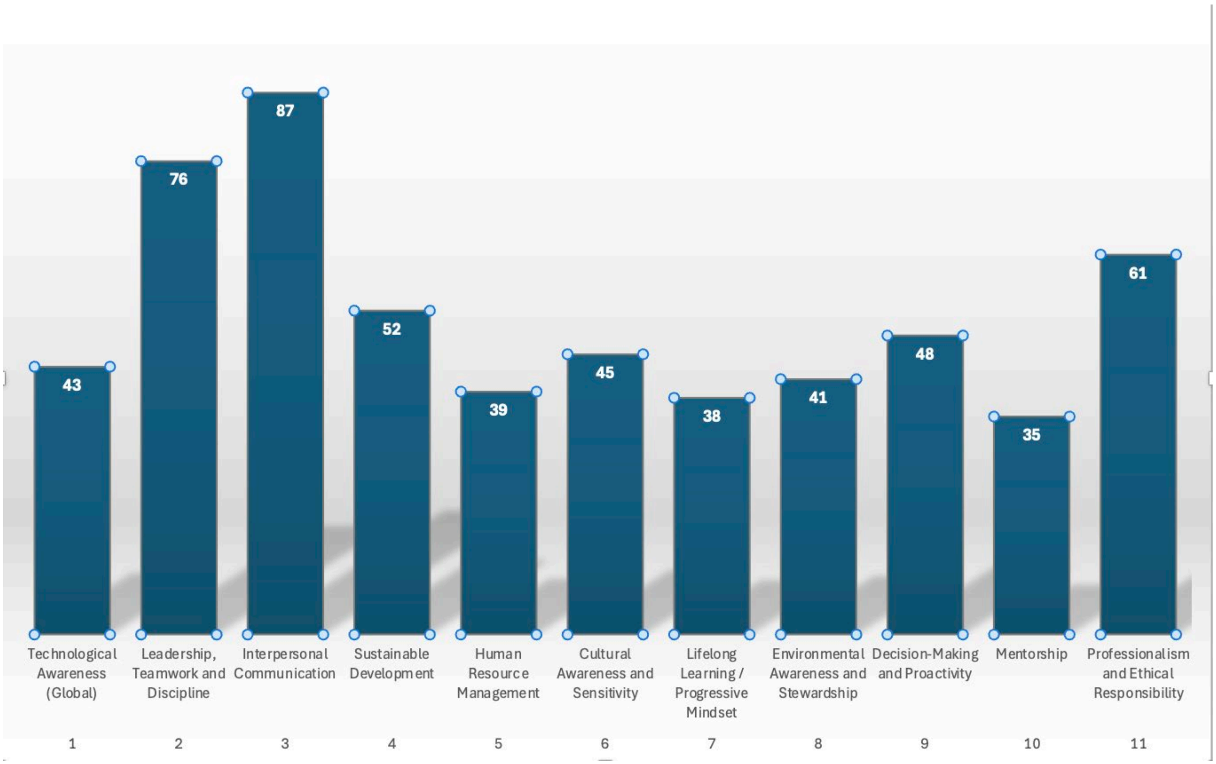
Each activity was purposefully linked to one or more soft skill domains from the GMP BoK. Collectively, these activities provided cadets with experiential learning opportunities that were emotionally engaging, socially interactive, and cognitively demanding – conditions proven essential for effective affective learning [5][6].

3. RESULTS

The empirical data collected from 553 cadets over a six-year period (2019–2025) demonstrates substantial and multi-dimensional development of soft skills in accordance with Tier A affective learning outcomes outlined in the GMP Body of Knowledge [1]. The cadets showed measurable progress across all eleven soft skill domains, including interpersonal communication, leadership and teamwork, ethical responsibility, cultural sensitivity, sustainable development, environmental awareness, human resource management, mentorship, technological awareness, decision-making, and a progressive learning mindset. These gains were evidenced through a combination of self-assessments, reflective journals, instructor observations, and psychometric diagnostics.

Graph 1 provides a comprehensive visualisation of cadet-reported growth across all soft skill categories. Interpersonal communication emerged as the most significantly developed area, with 87% of cadets indicating notable improvement, particularly through COIL activities and multilingual engagement. Leadership and teamwork followed closely at 76%, driven by team-based simulations and interactive workshops. Professionalism and ethical responsibility also demonstrated strong results at 61%, supported by reflective essays and ethical discussion sessions. Sustainable development achieved 52%, associated with cadet involvement in eco-focused hackathons and webinars.

Moderate but meaningful progress was reported in decision-making and proactivity (48%), cultural sensitivity (45%), and technological awareness (43%), primarily as a result of role-based learning and digital collaboration platforms. Meanwhile, growth in areas such as environmental awareness (41%), HR management (39%), lifelong learning mindset (38%), and mentorship (35%) reflected cadets' emerging behavioural adaptations rather than fully internalised values. These domains were more commonly expressed in longitudinal feedback and peer support practices.



Graph 1 Reported Development Across 11 GMP BoK Soft Skill Domains (2019–2025)

Source**:** Author's research

Overall, these findings confirm that a well-structured and thematically diversified extracurricular programme can facilitate progressive development of all GMP BoK soft skills. Notably, cadets who engaged in multiple types of activities (e.g., both collaborative and reflective) displayed broader and more sustained affective engagement, supporting the link between varied experiential exposure and deeper learning [5].

In addition to self-reported progress and observational data, the affective development of cadets was further examined using a structured analytical framework based on the three-tier taxonomy proposed in the GMP BoK: *awareness (receiving)*, *reflection-in-action (responding)*, and *value internalisation (valuing)* [1]. This framework allowed for the categorisation of cadet engagement according to progressively deeper levels of affective learning, as manifested in their behaviours, reflections, and task performance during extracurricular activities.

Table 2 presented selected examples of soft skill progression across all eleven focus areas identified in the GMP BoK. Each domain was mapped to a corresponding affective learning tier, with activity-based indicators drawn from cadet participation in COIL projects, workshops, poster sessions, innovation sprints, and reflective journaling. The model demonstrated how cadets progressed from conceptual recognition of soft skill importance to consistent value-driven behaviour aligned with professional standards.

Table 2 Soft Skills Competency Progression Based on GMP BoK Tier A (Selected Examples)

Focus Area (GMP BoK)	*Awareness (Receiving)*	*Reflection-in-Action (Responding)*	*Value Internalization (Valuing)*
Technological Awareness (Global)	Awareness of the role of technology in global shipping	Use of digital tools in learning projects	Initiating technical improvements to enhance efficiency
Leadership, Teamwork and Discipline	Understanding of leadership, teamwork, and discipline	Participation in group projects with role allocation	Taking leadership roles and mentoring others in teams
Interpersonal Communication	Identifying principles of effective communication	Practicing strategies for professional communication	Demonstrating active listening and managing communication barriers
Sustainable Development	Understanding the goals of sustainable maritime development	Attending webinars on sustainability	Integrating sustainability into personal academic or volunteer projects
Human Resource Management	Awareness of the role of HR in safety and performance	Participating in delegation of responsibilities	Supporting collaborative communication and task delegation
Cultural Awareness and Sensitivity	Recognition of cultural diversity	Engaging in intercultural case discussions during COIL projects	Respecting cultural nuances in decision-making and communication
Lifelong Learning / Progressive Mindset	Awareness of the need for continuous education	Active involvement in informal learning	Promoting self-learning and encouraging the growth of others
Environmental Awareness and Stewardship	Understanding of ecological challenges and impacts	Designing extracurricular eco-projects	Leading sustainability-oriented initiatives
Decision-Making and Proactivity	Realization of the importance of responsible decisions	Engaging in debate and analysis of alternatives	Making quick and responsible decisions during simulated crisis scenarios
Mentorship	Understanding the mentor's role in professional growth	Conducting onboarding or peer guidance activities	Inspiring and motivating younger cadets through informal leadership
Professionalism and Ethical Responsibility	Understanding professional ethics and standards	Participating in ethical discussions and applying codes of conduct	Demonstrating ethical leadership even in the absence of formal rules

Source: Author's database and adapted from the GMP Body of Knowledge (IAMU, 2019) [1].

This table highlights that cadet not only acquired knowledge of soft skills but also transitioned through observable phases of application and internalisation. For instance, in the domain of interpersonal communication, cadets evolved from identifying communication principles to actively applying strategies in multilingual contexts, and ultimately to demonstrating empathic listening and barrier mitigation. Similarly, in the domain of ethical responsibility, cadets moved beyond awareness of professional codes to autonomous ethical decision-making even in the absence of explicit guidance.

Such evidence confirms that a well-structured and thematically diversified extracurricular programme can facilitate progressive development of all GMP BoK soft skills. Notably, cadets who engaged in multiple types of activities (e.g., both collaborative and reflective) displayed broader and more sustained affective engagement, supporting the link between varied experiential exposure and deeper learning [5].

To further contextualise this progression, Table 3 synthesises the learning environments and formats most closely associated with the reported development in each of the eleven soft skill domains. This mapping provides insight into which types of extracurricular interventions are most effective in promoting specific competencies, offering practical guidance for programme design and pedagogical alignment.

Table 3 Learning Contexts Associated with Reported Soft Skill Development

№	GMP BoK Soft Skill Domain	Learning Contexts and Activity Types
1	Technological Awareness (Global)	Use of digital tools during international teamwork and collaborative platforms
2	Leadership, Teamwork and Discipline	Team-based quests, group role assignments, workshops on leadership
3	Interpersonal Communication	Gains in cross-cultural and multilingual communication, COIL projects
4	Sustainable Development	Participation in hackathons and webinars on sustainability and environmental topics
5	Human Resource Management	Group facilitation, responsibility delegation, role dynamics in simulations
6	Cultural Awareness and Sensitivity	Engaged in COIL-based multicultural tasks and reflection on cultural differences
7	Lifelong Learning / Progressive Mindset	Voluntary participation in webinars, self-directed learning behaviour
8	Environmental Awareness and Stewardship	Eco-projects, sustainability poster sessions, innovation sprints
9	Decision-Making and Proactivity	Crisis simulations, quests involving strategic planning and action under time limits
10	Mentorship	Peer support, onboarding activities initiated by senior cadets
11	Professionalism and Ethical Responsibility	Reflections on ethical codes, decision-making integrity in uncertain contexts

Source: Synthesised from author's activity reports and qualitative coding of cadet reflections (2019–2025)

4. DISCUSSION

The present study provides substantive evidence that extracurricular programming, when aligned with the GMP BoK affective framework, can serve as a strategic mechanism for developing the soft skill competencies expected of global maritime professionals. Rather than reinforcing cognitive outcomes alone, the implementation of structured, thematically coherent extracurricular activities enabled cadets to engage in value-based learning experiences that extend beyond formal instruction. This confirms the critical role of affective learning in maritime competence formation and challenges traditional views that such learning is peripheral or informal.

Crucially, the study reinforces the pedagogical validity of using a three-tier affective learning taxonomy – comprising *awareness*, *reflection-in-action*, and *value internalisation* – to scaffold the progression of soft skills. The mapping of cadet responses within this framework not only reflects measurable change in behaviour but also suggests a deeper integration of values, such as ethical reasoning, intercultural empathy, and collaborative discipline. These findings substantiate prior theoretical assertions that affective outcomes emerge not merely through exposure, but through *intentional structuring* of emotionally resonant, socially interactive, and professionally contextualised experiences.

The differentiated impact of activity types – such as COIL projects fostering intercultural communication, or scenario-based quests enhancing decision-making – highlights the need for deliberate activity – outcome alignment. In this regard, the study affirms the principle of *pedagogical specificity*: that no single format develops all soft skills equally, and that multimodal exposure is essential to comprehensive affective formation. Institutions should thus design portfolios of extracurricular interventions mapped to precise affective goals, rather than offering generic "soft skills training" without curricular integration.

Beyond the pedagogical domain, the study also reveals implications for institutional leadership. Maritime academies that aim to meet GMP BoK standards must move toward embedding soft skill development across their educational ecosystems, including in instructor training, assessment systems, and quality assurance frameworks. Doing so will not only align institutional outputs with international standards but also foster a more responsive and ethically grounded professional culture among graduates. The proposed mapping model offers a scalable template for such strategic integration and could inform accreditation protocols or internal programme reviews.

From a theoretical standpoint, the study contributes to ongoing efforts to reframe maritime education as a domain that synthesises technical proficiency with moral agency and humanistic intelligence. In contrast to conventional training models that prioritise compliance and procedural accuracy, this research illustrates how affective learning fosters adaptive professionalism, ethical reflexivity, and psychosocial maturity – attributes that are increasingly indispensable in a global, uncertain, and high-stakes operational environment.

The model outlined in this study offers a replicable framework for other Maritime Education and Training (MET) institutions seeking to enhance affective competencies without requiring extensive faculty specialization. Its modular and scalable nature allows adaptation across contexts, particularly in environments with limited access to specialized instructors.

To ensure alignment between the research findings and the study's guiding questions, the following insights are drawn in direct response to the initial research aims:

Firstly, regarding the motivations behind cadet participation in extracurricular activities, data from reflective journals and voluntary engagement indicate that intrinsic factors – such as a desire for international collaboration, leadership growth, and ethical competence – served as primary motivators. The absence of grading or formal rewards further supports the authenticity of their participation.

Secondly, concerning the extent to which these activities supported Tier A affective learning outcomes, the collected data clearly demonstrate that structured extracurricular formats – especially COIL projects, scenario-based quests, and interactive workshops – contributed to measurable skill development. These included leadership, communication, decision-making, and ethical responsibility, in line with the GMP BoK affective descriptors.

Thirdly, in terms of how cadets perceive the personal and professional impact of their involvement, qualitative and quantitative feedback reflected increased self-confidence, stronger professional identity, and a heightened sense of preparedness for ethical and multicultural challenges. This suggests not only behavioural change but also deeper value internalisation.

It is also important to note that the GMP BoK is currently undergoing revision, with an updated edition expected by the end of 2025. Future adaptations of extracurricular programming should remain flexible and responsive to evolving competencies and focus areas outlined in the forthcoming framework.

5. CONCLUSIONS

This study demonstrates that extracurricular activities, when systematically aligned with the Global Maritime Professional Body of Knowledge (GMP BoK), are a viable and impactful method for cultivating affective competencies in maritime cadets. The integration of diverse, interdisciplinary, and reflective learning formats significantly contributed to the development of soft skills across all eleven GMP-defined domains, including leadership, ethical responsibility, intercultural communication, and decision-making.

By adopting a mixed-methods research design – combining surveys, psychometric profiling, self-assessment, and direct observation – the study captured both observable behaviours and internalised values. The structured application of a three-tier affective taxonomy allowed for detailed tracing of cadet progression from initial awareness to value-driven actions. This evidence base not only validates the pedagogical effectiveness of such interventions but also underscores their strategic relevance in the context of global maritime standards.

A key outcome of the study is the demonstration that affective learning is neither incidental nor spontaneous; rather, it must be intentionally embedded within the educational design. The cadets' sustained affective engagement and behavioural transformation were most evident in programmes that combined collaborative, intercultural, and ethically challenging dimensions. This highlights the critical need for differentiated purpose-driven extracurricular formats mapped to specific soft skill domains.

From a managerial and institutional perspective, the findings call for a reconfiguration of how maritime training institutions conceptualise and implement soft skills development. The mapping framework developed through this research offers a practical tool for curriculum designers and administrators to plan, evaluate, and scale affective learning interventions in line with the GMP BoK framework.

In theoretical terms, the study contributes to a growing body of literature that situates affective competence at the heart of professional maritime education. It advances the understanding that truly global maritime professionals are not only technically skilled but also ethically grounded, culturally competent, and socially adaptable.

Therefore, maritime education providers should prioritise the systematic integration of soft skill outcomes – such as those demonstrated in this study – into both formal curricula and institutional strategy. Doing so will ensure that graduates are not only operationally effective, but also capable of contributing to the sustainability, safety, and ethical leadership of the maritime industry in the decades to come.

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ANALYSIS OF THE CMMS DATABASE

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Abstract

Maintenance is a process that requires good organization of resources, spare parts and personnel. In order to better organize maintenance in companies in the maritime sector, planned maintenance was introduced. The system has been continuously developed and has evolved over time into a Computerized Maintenance Management System (CMMS), the most important organizational form of planned maintenance in the maritime sector. To support this role, commercial CMMS programs have been developed and sold on the market. This paper analyzes an example where a company does not have a sufficiently developed system for planned maintenance and examines what solutions could be implemented using the available tools. Using an Excel file available to the company as part of the Microsoft Office package and using their own resources to create a computer database, a proposal was made for the creation of their own unique CMMS. This analysis shows a small sample of the company's system, which contains several thousand pieces of information. A cross-sectional analysis shows that the system is fully functional and can meet the company's requirements. The price that would have to be paid is the time that would be spent on data entry and configuring the program. Comparing this approach with competing commercial CMMS programs, the result is clear and complete. The proposed in-house system is cheaper, meets the company's needs and is tailored to its requirements, but does not have all the features that commercial CMMS programs offer and requires constant employee involvement in its development and improvement.

Keywords: maintenance; buoys; CMMS; data analysis

1. INTRODUCTION

Maintenance is a field of technology composed of technical skills, techniques, methods and theories, all aimed at "*keeping the wheels in our society rolling properly*" [5]. It is about finding both technical and organisational solutions to ensure that facilities operate properly, cost-effectively, with low energy consumption, without polluting the environment and in a safe, controlled and predictable manner [2, 5].

Apart from corrective maintenance, maintenance management is usually divided into three basic principles: Run-to-failure (repairs maintenance), preventive and predictive [12]:

- The Run-to-failure (repairs maintenance) logic is very clear and simple. In the event of a failure, a repair is required. However, if the machines or devices are not defective, repair is not required. This method is based on a response that waits until a machine or device fails before initiating a maintenance action. It is a maintenance-free management concept that is also the most expensive. An extremely important factor in this type of maintenance is the availability of personnel who can respond quickly and of spare parts. This can be achieved through extensive stockpiling of parts (or at least critical equipment). The alternative is to rely on suppliers who can deliver the parts reliably and immediately [12, 13].
- Preventive maintenance, also known as planned maintenance, was introduced in 1950 and is based on time-based maintenance. The basic principle is that it comprises predetermined shutdown measures that result from the functionality of the machine or system and the service life of the components. The probability of failure after the normal service life is relatively low if maintenance is carried out; after this normal service life, the probability of failure increases sharply. Companies usually formulate preventive maintenance and repair schedules based on past experience and common practices [3, 8, 13].
- The common premise of predictive maintenance is that regular monitoring of the mechanical condition of machine trains ensures a maximum interval between repairs and minimizes the number and cost of unplanned outages due to machine train failures. Simply put, the actual operating condition of the systems and machines is used. This method is based on diagnosis-based maintenance (condition monitoring) and prognosis-based maintenance (reliability-oriented). It is the most advanced maintenance method, as vibration analyzes, thermography, ultrasound monitoring, oil analyzes, etc. are carried out. Recurring and high-risk failures are analyzed based on historical data [3, 11, 13].

The analysis of maintenance costs shows that a repair carried out in a reactive or "run-to-failure" operating mode is on average around three times as expensive as the same repair carried out in a planned or preventive operating mode [13].

The maintenance of navigation safety objects is one of the key factors for maintaining the safety and functionality of maritime traffic. Given the organizational and technical complexity, the systems for managing these assets are often limited to static displays or administrative registers that are unable to dynamically monitoring maintenance and costs.

The company responsible for the maintenance of waterways, radio traffic and navigation safety installations in the Adriatic uses the developed “Register of Navigation Safety Installations”, which provides information about the installations in the territorial sea and in the economic zone of the Republic of Croatia via a geographical browser. The system enables the digital recording and reporting of defects and is based on the principle of preventive maintenance. However, the functionality of the system is limited in the area of planned maintenance management [14].

In this context, the paper explores the possibilities of system improvement through the application of modern approaches to maintenance management, focusing on the integration of computer tools for the planning and optimization of maintenance activities.

The aim of the paper is to present the possible solution for deficiencies in the area of planned maintenance and to determine the functionality of this solution, to compare it with other possible solutions and to draw a conclusion about the appropriateness of the applied solution and possible improvements.

2. COMPANY COMPUTERIZED SYSTEM

The computer system "Register of Navigation Safety Installations" is a digital interactive platform developed by the company to visualize the entire system of navigation safety installations in inland waters, territorial sea and the exclusive economic zone of the Republic of Croatia.

In addition to visualizing the system of navigational safety installations in the form of an interactive GIS (geographic information system) browser, the platform allows users to report incidents of navigational safety installations and register navigational safety installations via digital forms:

The malfunction report form allows users to report problems with navigational safety equipment and describe the nature of the damage in more detail. It is divided into several sections in which personal data about the reporter (private individual or ship, if applicable), data about the malfunction report, data about the identification and characteristics of the navigational safety equipment and data about malfunctions in the operation of the equipment are recorded. This is to ensure that the reported damage is rectified quickly and efficiently in order to maintain the safety of navigation without interruption.

With the reporting form for navigation safety equipment, the most important data on the equipment can be entered for recording and further monitoring. It is possible to enter basic information about the object, with the option of attaching photos, a detailed description of the navigation and administrative data [14].

2.1. Buoys in the computerized system – Interactive geographic information system (GIS) viewer

The interactive GIS viewer is a central element of the register of navigation safety objects. Directly through the interface, the viewer provides users with basic and navigational data on each individual object, including technical characteristics and operational status. This viewer is an important tool for seafarers, competent institutions and experts in the field of maritime safety, ensuring transparency and up-to-date data necessary for safe and efficient navigation. Among other things, the company's system includes a buoy description system. Figure 1 shows a list of buoys that can be found on the subpage on this topic [14].

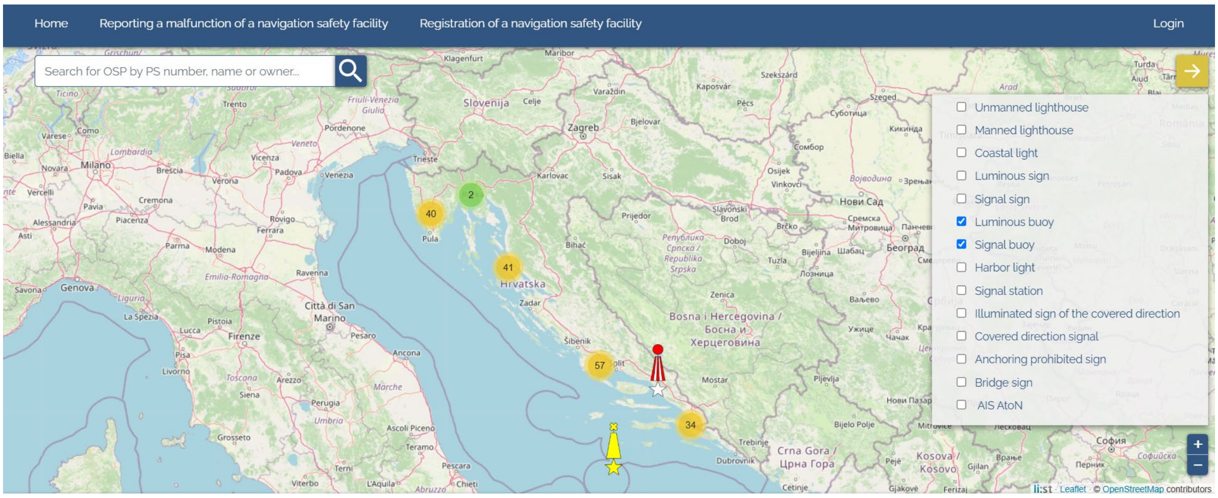

Figure 1 Interactive GIS viewer of the Register of Navigation Safety Facilities [14]

The navigation system offers the option of selecting individual objects and displaying object details such as basic data and navigation data. Figure 2 shows a light buoy located 500 meters north of the coastal beacon with the number "562", with the option to select detailed data.

Figure 2 Example of Light Buoy (PS No. 562) [14]

Figure 3 shows an information display of the interactive browser, which in this case contains detailed data about the previously mentioned light buoy. The basic data shows data such as the name, the unique number and the serial number from the list of light and fog signals. The physical appearance of the buoy is described with a top sign and it is indicated whether the object is in the remote monitoring system. Further information such as navigation data (geographical position), coordinates, category, classification, object status and light characteristics are also provided. The range of the light in nautical miles, the colour of the buoy and whether the object has a radar reflector and retroreflective markings are also included.

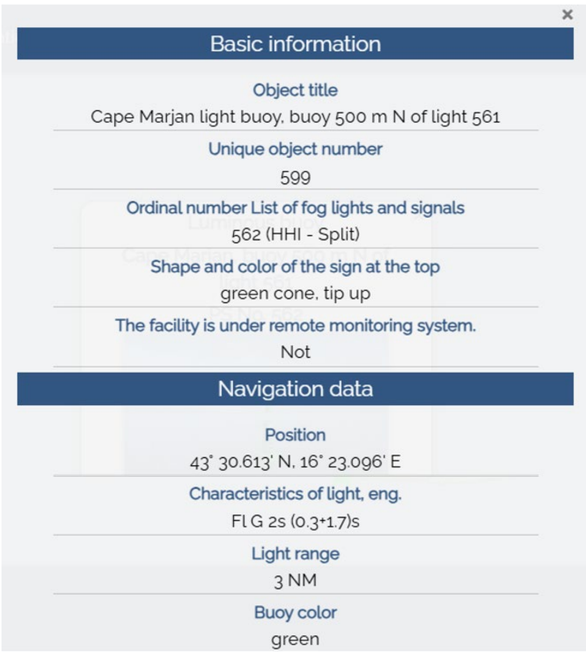

Figure 3 Part of details of Light Buoy [14]

2.2. Missing item in analysed computer system

When analyzing the system presented, it is found that the available data on the objects is of great importance, but does not answer some of the following questions:

- When is the next buoy maintenance scheduled?
- What was the last fault and how was it rectified?
- How often does an intervention need to be carried out on the buoy?
- How much money has been spent on repairs to this buoy in one or more years, and is there a spreadsheet of the costs?
- What are the average maintenance costs per buoy per year?
- Is there a warranty for the buoy or its individual parts?

From the above questions, it appears that the system is missing an additional part that would answer the questions posed, allow for more advanced maintenance management (like [10, 15]) and possibly reduce the number of buoy failures through better preventive maintenance monitoring. Such systems were called "Planned Maintenance Systems" (PMS) when their purpose was to organize the maintenance of plants [1, 17].

Today they are called "Computerized Maintenance Management Systems" (CMMS) and comprise a unified management system for the entire ship (crew, safety, security, documents, dry dock, purchasing, budgeting, accounting, etc.), not just for maintenance [18].

3. PROBLEM SOLLUTIONS

3.1. History of the Planned Maintenance System

The concept of Planned Maintenance was first introduced in 1915 by Christensen & Co., which operated the largest whaling fleet in the world at the time. Although it remains unclear who originally invented the system, credit is often given to Arnesen Christensen & Co. The initial system was managed manually, recorded on paper, and included only a few of the most critical ship components. Over time, the system evolved and expanded. By 1950, Christensen & Co. had developed the first comprehensive, written Planned Maintenance program for ships. In 1963, Anthony J. Ruffini further advanced the concept by establishing the Planned Maintenance System for the U.S. Navy. The development of computers later provided a significant boost to Planned Maintenance programs in shipping. In 1984, the first software specifically designed for ship maintenance, called the Asset Management Operating System (AMOS-D), was released. The emergence of Windows-based software further accelerated the development and adoption of Planned Maintenance systems, leading to a wide range of digital solutions now available for the maritime industry [6, 7, 19].

3.1.1. How to solve the problem

The shortcomings listed under 2.2. of this article can be remedied in various ways. In view of the historical facts, the first option is the most difficult to implement and monitor, namely the system in written (paper) form. This system is based on manual records in books, notebooks and tables. A major disadvantage of such a system is its lack of clarity, which can lead to data loss and difficulties in analysis.

Another option is the Computerized Maintenance Management Systems (CMMS). CMMS is a tool for improving maintenance management. The system provides a common platform for the implementation of strategies in all departments of the company. It must be set up properly, complying with company policies and procedures and ensuring a satisfactory output database. It is a software system that centralizes maintenance data and simplifies processes in the form of planning, tracking, reporting on completed tasks, managing work orders and scheduling upcoming maintenance work. The functions of such a system also enable the management of resources and inventories, the analysis of costs, performance, efficiency in the execution of tasks, etc. The system is assigned functions such as asset management, work orders, preventive maintenance and reporting, and inventory control. It also provides easy access to historical data and generates reports on the work carried out [9, 20].

3.2. Proposed solution

Based on the facts mentioned in 2.2. and at the beginning of this chapter, after analyzing commercial CMMS and guided by the conclusion that these are not perfectly tailored to the specifics of the company, it is proposed to develop a company's own CMMS. The "future" company's CMMS, shown in the figures below, will serve as the basic tool for managing the planned maintenance of sea buoys. The system is a detailed register that combines operational, technical and financial information to enable systematic, timely and cost-effective maintenance. The system has been developed using Microsoft Excel, which is part of the standard software package that the company already uses. Excel is the most commonly used DataBase Management System (DBMS) with many possibilities, but also with some limitations. The spreadsheet contains several sheets that together form the CMMS; the first two are called "Buoy data" and "Pivot Table - Costs".

3.2.1. Sheet "Buoy data"

"Buoy data" subpage in Excel contains a catalogue and a list of the buoys with their detailed data as well as the structural data. Figure 4. show the data of four buoys randomly selected to analyse the data system. The sheet labelled "Buoy data" centralizes the data in the CMMS system. Each row represents a single buoy and the columns contain important technical, geographical and operational information. This structure enables precise technical and logistical control over each buoy within the system and supports efficient management of planned maintenance. Analyzing the sheet shown, each column shows the following data like serial number in the database, sea area, buoy name, buoy number, object type, (region A), colour, shape of the buoy, topmark, light (if available), rhythmic character, light range, AIS AtoN, radar reflector, purpose (only for special marks), buoy type, depth, length of anchor line, year of installation, technical data sheet, warnings before next maintenance, date of last maintenance, frequency of maintenance (years).

Buoy data																			
No.	Sea area	Buoy name	Buoy number	Object type (Region A)	Colour	Shape of buoy	Topmark	Light (when fitted)	Rhythmic character	Light range	AIS AtoN	Radar reflector	Purpose (only for specal marks)	Buoy type	Depth	Anchor line length	Year of installation	Technical sheet
122	Split	Cape Marjan, buoy 500 m N of light 561	562	Lateral mark (Starboard hand)	Green	Pillar	Single green cone, point upward	Green	Fl G 2s (0,3+1,7)s	3 NM	YES	YES	Not appicable	Mobilis, JET 2500Q PF3	12 m	33 m	2020	Adobe Acrobat Document
123	Split	Island of Čiovo, Cape Okruk	536	Lateral mark (Starboard hand)	Green	Pillar	Single green cone, point upward	Green	Fl G 3s (0.3+2.7)s	4 NM	NO	NO	Not appicable	Tideland SB-138P	14 m		2022	Adobe Acrobat Document
124	Split	Duilovo	570,03	Special mark	Yellow	Spar	Single yellow "X" shape	Yellow	Fl Y 5s (0,5+4,5)s	3 NM	NO	YES	Wastewater mark	Mobilis, BC 1500	28 m	60 m	2023	
125	Split	Trogir E, buoy no. 2	542,4	Lateral mark (Port hand)	Red	Pillar	Not fitted	Red	Fl(2) R 5s (0,5+1;0,5+3)s	4 NM	YES	YES	Not appicable	Mobilis, Module 1200	5 m	12 m	2018	Adobe Acrobat Document

Figure 4 The first part of Buoy data subpage

The buoy maintenance (Figure 5.) is part of the same subpage in Excel that continues the Table shown in Figure 4. The maintenance is linked to the same serial number in the database to which the data on planned work on the specified device is linked. The "Warning" field is a field that indicates the maintenance status with colour and text (red - overdue; orange - due, green - OK). This is followed by the frequency, which is also color-coded.

Maintenance				Buoy maintenance checklist		
Warnings about the next maintenance	Date of last maintenance	Frequency of maintenance (years)	Date of planned maintenance	2024. year	2025. year	2026. year
Service required!	11 May 2024	1	11 May 2025	MAINTENANCE CHECKLIST 11. 5. 2024.		
Service required!	01 February 2024	1	01 February 2025	MAINTENANCE CHECKLIST 1. 2. 2024.		
OK	06 September 2024	1	06 September 2025	MAINTENANCE CHECKLIST 6. 9. 2024.		
OK	15 February 2025	1	15 February 2026	MAINTENANCE CHECKLIST 16. 2. 2024.	MAINTENANCE CHECKLIST 15. 2. 2025.	

Figure 5 The second part of Buoy data subpage

As part of the digitization of planned maintenance, the CMMS is integrated into the Microsoft OneDrive storage. After completing regular maintenance and interventions on a specific buoy, ship masters and navigation officers fill out a standardized "Buoy Maintenance Checklist" in Microsoft Word format, which they attach within the CMMS in the form of a link (hyperlink). Once the document is attached, it is immediately visible to managers and other responsible persons and provides insight into buoy maintenance status without the need to send inquiries to field offices (vessels). Storage enables efficient connection of vessel crews and supervising management via 'cloud' technology and speeds up the completion of work orders and cost records. It is important that a written record of the last maintenance is kept in one place with regular maintenance dates and additional crew notes, allowing for better planning of subsequent services. This page allows a quick and easily check work orders and their planning as well as an overview of previous orders on the equipment.

The amount of data on this subpage grows daily. The amount of data on the subpage as of April 23, 2025 is shown in Table 1.

Table 1 Quantification of the data on the "Buoy data" subpage on April 23, 2025.

Rows	Columns	Attached .pdf files	Attached .doc files	Total amount of data	Missing data
178	26	154	191	4215	50

3.2.2. Sheet "Pivot table - Costs"

By introducing the structured pivot table "Pivot table - Costs " for recording and analyzing maintenance costs and the associated graph, that contributes to the clarity of data interpretation, the company realizes functional and strategic advantages in the management of the technical systems of navigation safety. The primary goal of the table is to provide a visual understanding of the cost structure and enable managers and other authorized individuals to extract key information relevant to operational and strategic decision making from a large amount of data using a two-dimensional bar chart (Figure 6.). The diagram shows randomly selected buoys from point 3.2.1 of this article.

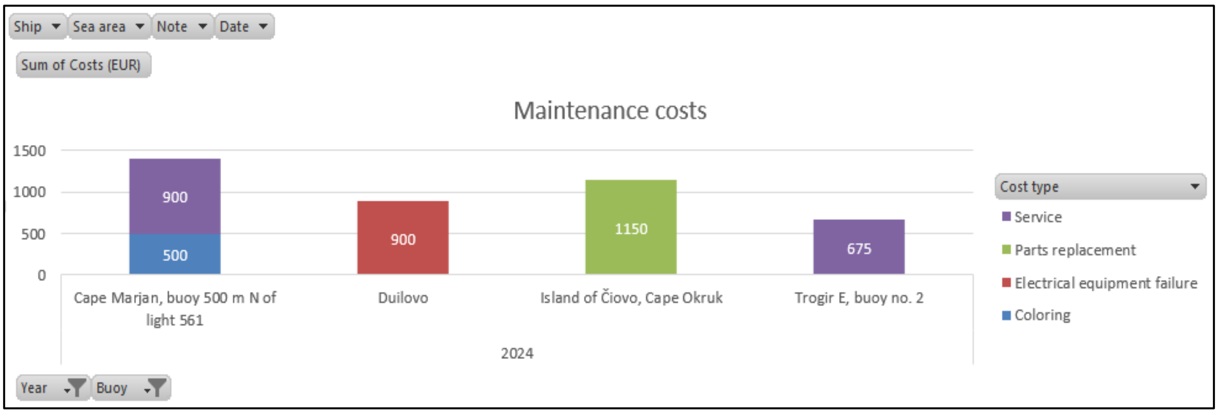

Figure 6 Buoy maintenance costs

The costs are classified according to the type of disturbance, the name of the buoy, the sea area and the field unit (ship) that carried out the work. This overview provides the company with a detailed insight into the costs categorized by individual buoys and the type of intervention (regular maintenance, replacement of parts, painting, electrical equipment failure, etc.), as well as accurate planning of upcoming costs in the form of spare parts procurement and resource planning. With a simple insight into costs, the company is able to identify recurring problems. Data analysis makes it possible to identify which buoys require frequent interventions, which opens up scope for defining maintenance strategies and technical optimizations. It also shows which types of failures occur most frequently and which buoys generate the highest costs. In addition, this form of analysis enables dynamic filtering and grouping of data, which simplifies and speeds up access to information that later forms the basis for the organization of planned voyages, spare parts logistics and personnel management. The spreadsheet also allows managers to predict future costs based on real data and create realistic annual budgets for their fleet.

The amount of data on this subpage, as well as on the first subpage, will grow daily. The amount of data on the subpage as of April 23, 2025 is shown in Table 2.

Table 2 Quantification of the data on the "Pivot table – Costs" subpage on April 23, 2025.

Element	Amount of the same data	Description	Amount of different data
Date	151	Every working day	197
Year	2	2024, 2025	197
Buoy	176	Every buoy	197
Ship	3	M/V "Vessel 1", M/V "Vessel 2", M/V "Vessel 3"	197
Cost type	6	Service, buoy damage, parts replacement, electrical equipment failure, coloring, buoy positioning	197
Costs (EUR)	147	Every individual cost	197
Sea area	7	Dubrovnik, Korčula, Pula, Rijeka, Split, Šibenik, Zadar	197
Note	2	Regular maintenance, intervention	197
		Total	1576

The total number of data on the first two pages of the Excel file is the sum of the data listed in Tables 1 and 2 and amounts to more than 5700 information, which are likely to increase daily.

3.3. Commercial CMMS

As mentioned in subsection 3.1., another way to solve this problem is to purchase and install a commercial computer program [4, 16]. An example of a database area in such a program is shown in Figures 7 and 8.

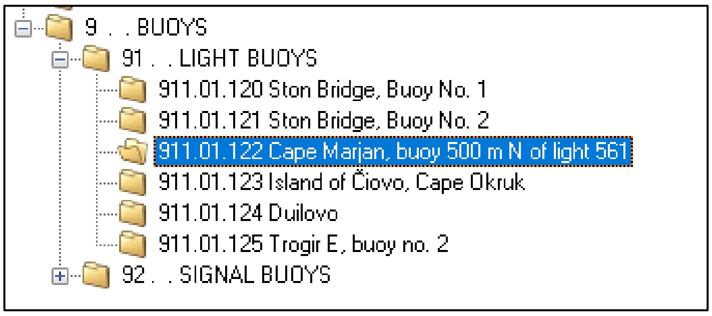

Figure 7 Example of buoys in commercial CMMS

Figure 7 shows a list of all buoys in the program. When one of them is selected in the buoy tree (as in Figure 7.), the buoy details shown in Figure 8 appear on the right side of the screen. On the right-hand side of the screen of a commercial CMMS, in addition to the directly visible data, there are a series of sub-pages where the corresponding data is entered. Number 1 is the sub-page with the details of the buoy, such as the technical data. The sub-page with the number 2 describes the details; here you can assign several jobs to one buoy. Sub-page 3 lists all spare parts (if available), their stock and the storage location of the parts (ship or shore storage). Subpages 4 and 5 are used for reporting on completed work, keeping maintenance logs and attaching images and forms.

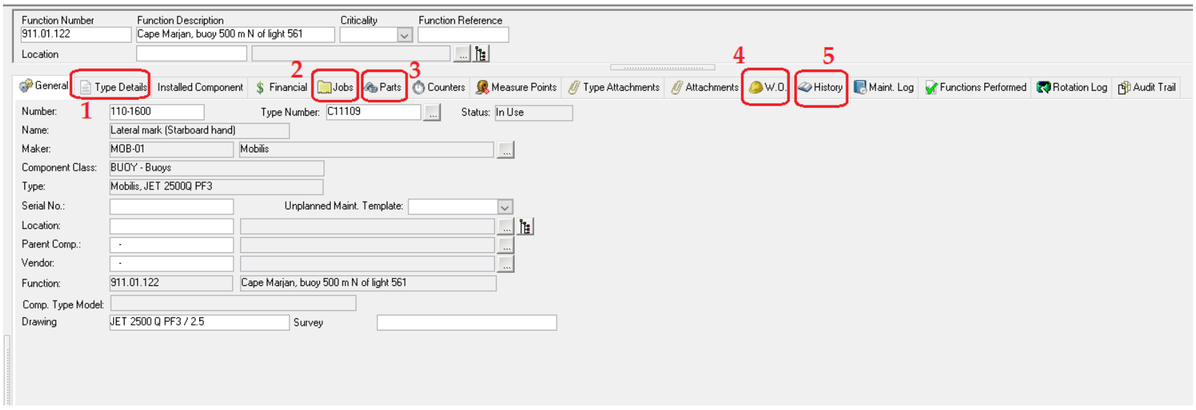

Figure 8 Example of buoys data in commercial CMMS

This entire commercial CMMS package has its price. Figure 9 shows the cost of such a program.

1. Office Licence	15.000 €
2. Vessel Licence (per vessel)	7.900 €
3. Database (proportional to size)	6.000 – 10.000 €
4. Annual (maintenance) fee	20 % of the Licences (Office + vessels)

Figure 9 CMMS costs (Source data withdrawn)

4. ANALYSIS AND COMPARISON

4.1. Advantages of self-developed systems

Advantages of the self-developed systems:

- Implementing the system does not require the extensive external resources needed to implement a commercial CMMS, but rather the commitment, dedication and knowledge of the company's employees. The development of the system, from business requirements to analysis, customization and testing, is done exclusively by the company's employees. This fosters a culture of collaboration and innovation.
- Employees are very familiar with the system.
- Full customization to business processes and company requirements with unique maintenance processes, without unnecessary features that would make the system difficult to use.
- No additional license costs compared to commercial CMMS, nor any annual fee.
- The company has full control over the system and its sensitive data, as well as the ability to further develop, maintain and update the system.
- Easy integration with internal systems.
- The ability to implement operational security measures in the form of health and safety and handling safety devices.
- Process automation enables quick, easy and accurately planned maintenance of equipment in a given period. Planning accuracy optimizes the work of the teams and the use of resources for equipment maintenance of the equipment and reduces the cost of the maintenance itself.

- Continuous adaptation to new challenges and regulations without dependence on third parties.
- The system can be developed according to the company's needs, without the limitations often present in commercial CMMS.

4.2. Advantages commercial solution

Commercial solutions have many advantages over self-developed systems. They are:

- Commercial CMMS offer ready-made solutions, i.e. they are already developed and ready to use, making them easy to implement.
- They are regularly updated and cyber security is reinforced.
- The creation of databases is usually done by professionals, which leads to better quality.
- Commercial systems often comply with ISO standards and other regulations.
- Users have the opportunity to get help from experts and other users who are using the same system.
- Such systems offer the possibility of training and user certification.
- Modern systems can be used not only via a computer, but also via various electronic devices such as cell phones, laptops and tablets.
- It enables the assignment and managed of different access rights depending on the business roles of employees.
- It has advanced features such as a filter for maintenance periods (Figure 10).

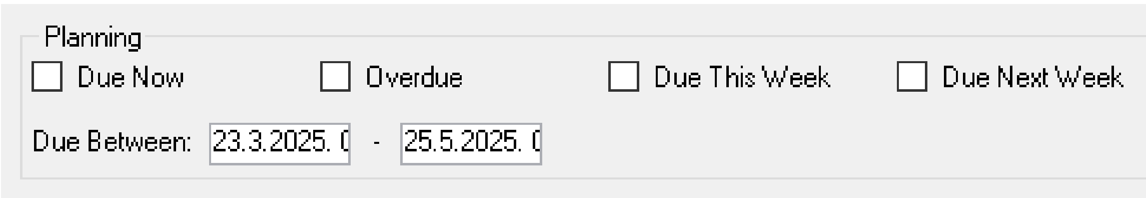

Figure 10 Filter for maintenance between periods

5. CONCLUSION

As highlighted in Chapter 2.2, the proposed internal solution should provide answers to the following questions: When is the next buoy maintenance due; what was the last failure and how was it fixed; how often does the buoy need maintenance; how much money has been spent on repairs to this buoy in one or more years, and is there a spreadsheet with the costs, etc. The presented solution, which was created using simple means (Excel as a basic DBMS) and the knowledge of the company's employees, was able to answer all questions and was successfully implemented in the examined company. During the creation of the database and the development of the system, the employees were trained in the use of the system and can fully meet the requirements of the company. In addition, the employees have entered more than 5700 pieces of information into the system, so they are familiar with modifying and expanding the database.

Could it have been done differently and better? Chapter 3.3. presents a different solution, namely a commercial program that would solve the problem "better". This program (and others of its kind) would be delivered as a ready-made solution, and the database would be created by specialized personnel in a database factory. In addition, the company would offer a guaranteed service and a service to expand the database (even on a daily basis). Of course, this has its own, non-negligible price, and it is questionable whether the company in question needs all the possibilities that such programs offer.

The conclusion from this analysis is simple. The company in question can get a solution that works and fulfils all its requirements with a self-developed solution. There is no need to spend money on buying a commercial program (employee training, database creation, annual license), and the price you would pay is a slightly worse functionality of this kind of solution. Can a better solution be created using our own employees? Perhaps yes, by using the Microsoft Access program, which is a bigger and better DBMS, but does not have a widespread network of users and is more difficult to program. In any case, this analysis shows that simple solutions are often the best.

Conflict of interest: All authors declare that they have no conflicts of interest.

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INTEGRATION MODEL OF AUTONOMOUS UNDERWATER VEHICLES AND UNMANNED AERIAL VEHICLES FOR COMBATING ILLEGAL, UNREPORTED AND UNREGULATED FISHING

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Abstract

Illegal, unreported and unregulated (IUU) fishing can pose a serious threat to biodiversity, maritime ecosystem and fish fonds that otherwise can be exploited in a more adequate and economical manners. Advanced fishing management techniques, enhanced algorithms, and newly developed technologies, more specifically the upswing of unmanned aerial vehicles (UAV) and autonomous underwater vehicles (AUV), can help provide new solutions to combat the illegal activities at sea. This paper aims to explore the current findings regarding usage of UAVs and AUVs for abundance assessments and direct and indirect prevention of illegal, unreported, and unregulated (IUU) fishing by applying thorough analysis, compilation, systematic comparison and evaluation of methods and technologies indispensable for creating a modern fishery management system supported by AUVs and UAVs. As the contribution, the paper proposes an integrated model for deterrence of maritime misconduct by combining UAV and AUV systems, as well as using them for localizing high-risk areas according to depletion of fish stock. In that way distributing resources in the appropriate areas for maximizing the efficiency of law enforcement efforts by various agencies operating underwater and aerial maritime drone systems. In addition, possible challenges and drawbacks of the system that will have to be addressed are also examined and explained. Limitations of the study include the fact that the model has not been implemented in practice, which opens the gates to further research and possible continuation and expansion of proposed integrated UAV and AUV IUU fishing prevention model.

Keywords: IUU fishing, sustainable fishing, AUV, UAV

1. INTRODUCTION

Illegal, unreported, and unregulated (IUU) fishing has been shown to have an increasingly detrimental impact on fish population abundance across various geographic regions. This escalating issue presents a significant challenge to traditional IUU combating methods, which may no longer be sufficient to address the complexity and scale of the problem [1–6]. In light of this, the current paper aims to examine the latest technological advancements, with a primary focus on the development and implementation of autonomous underwater vehicles (AUVs) and unmanned aerial vehicles (UAVs). These technologies are explored both in the context of fish stock abundance assessment and in the direct identification and catching of IUU vessels. Furthermore, this paper proposes a threshold-based algorithm designed to underpin an integrated operational model. This model links ecological data acquisition with enforcement actions, using the capabilities of AUVs and UAVs to create a responsive, data-driven system for monitoring and combating IUU fishing. The authors suggest this model as a means of improving efficiency and effectiveness in the deployment of available resources. The structure of the paper is organized into four main chapters, each addressing a key component of the proposed approach. The first chapter provides a detailed examination of fish stock population growth models and explores how these models relate to IUU catch estimation. It also delves into the role of AUVs and UAVs in conducting fish stock assessments, highlighting their contribution to the data needed for both population modelling and catch analysis. By establishing this foundation, the chapter emphasizes the importance of accurate, autonomous data collection as a basis for effective fisheries management and IUU monitoring. The second chapter shifts focus to the technological side of enforcement, exploring various emerging technologies used in the direct identification of IUU vessels. Special attention is given to advancements in computer-enhanced vision systems and vessel recognition models, which are proving to be increasingly useful in maritime surveillance. In addition, this chapter presents an overview of the unmanned platforms currently in operational use, detailing their technical characteristics in the context of maritime monitoring and enforcement missions. In the third chapter, the paper addresses the concept of maximum sustainable yield as a potential reference point for defining intervention thresholds within the proposed algorithm. It further elaborates on the design and theoretical structure of the algorithm itself, which is intended to serve as a flexible, scalable framework for integrating various unmanned and autonomous platforms. The aim of this integration is to enable a system capable of optimized resource allocation, deploying assets only when necessary and in areas where they will have the greatest impact, though this algorithm lacks practical implementation. Finally, the fourth chapter explores several challenges and limitations related to the real-world applicability of the technologies, models, and algorithms discussed throughout the paper. It acknowledges existing technical, logistical, and contextual constraints, and emphasizes the importance of continued research and development. The chapter concludes by outlining potential directions for future work, thereby opening the door for ongoing innovation and interdisciplinary collaboration in the field of sustainable fisheries management and IUU fishing prevention.

2. CONDUCTED RESEARCH ON FISH STOCK CONTROL

This chapter will examine the relation between fish stock population depletion and illegal and uncontrolled (IUU) fishing, as well as usage of unmanned aerial vehicles (UAVs) and autonomous underwater vehicles (AUVs) in determination of fish population quantity and in turn correlate the two phenomena whereby fish stock assessment can be used in IUU intensity assessment as well, providing state authorities with information for necessary reactive action-taking.

2.1. Impact of IUU fishing on fish stock

There are several examples of fish stock deterioration in certain geographical areas due to illegal and uncontrolled (IUU) fishing operations [1-6]. Examples of fish stock deterioration due to unlawful and uncontrolled activities mostly apply to the West and Central African coast, but there are also examples of this type of fishermen conduct affecting fish population in the Caspian Sea and Northern Africa [1-6]. Industrial IUU catching severely deteriorated fish stock population of Tunisia [3]. Stingrays and dolphins as well as other endangered species have also been noted to entangle in nets, while sea-grass beds are damaged from deep-water trawling [3]. In the Caspian Sea, the historically most important fish species, sturgeon, has been classified as critically endangered as a result of overfishing and destruction of spawning grounds [6]. IUU fishing has also had negative socio-economic impact on certain areas, for example in the case of Sierra Leone, artisanal fishing has been compromised by IUU fleet overexploitation of the area [1, 5]. In all cases, however, IUU fishing has negatively reflected on fish stock quotas and thus a correlation between stock depletion and an increase in IUU fishing activities can be drawn. Natural change of fish stock in one year in relation to quantifiable factors can mathematically be described using the following equation:

$$B_i = B_{i-1}e^{-F_{i-1}-M} + R, \qquad (1)$$

where B_i is the calculated biomass quantity for the current year, B_{i-1} is the biomass quantity of the previous year, F_{i-1} is expected mortality rate due to fishing, M is the natural mortality rate and R is the natural biomass increase. If the calculated biomass of the current year deviates from the measured one such that $B_{icalculated} > B_{imeasured}$ this could indicate the rise of mortality in previous year due to IUU fishing. Thus, the catch for the previous year can be calculated as [7]:

$$C_{i-1} = \frac{B_{i-1}F_{i-1}(1-e^{-F_{i-1}-M})}{F_{i-1}+M}, \qquad (2)$$

Consequentially, if the fishing mortality rate and catch quantity increases above the threshold of sustainability, the information could serve as an alarm to the authorities to start taking measures against IUU fishing.

2.2. Fish stock assessment using autonomous underwater vehicles

As articulated in the previous subchapter, for correctly assessing the need to deploy measures against the IUU fishing, law enforcement authorities must firstly be acquainted with the current fish stock status which must be measured and assessed in real time. Assessment of fish population quantity can never be fully precise, nor can an exact biomass ever be known, but close approximations are achievable using proper sampling procedures when assessing the fish stock. Usual unbiased procedure includes choosing a specific sampling area or areas at random from all the possible sampling sites. Apart from probability assessment, non-probability assessment may also be used in case of specific areas to which certain rare species are either linked or the areas themselves are limited, such as lakes, so there exists no need for probability sampling [8]. After selecting the sampling area, there are number of methods of assessing population on the spot. One of them is using autonomous underwater vehicles (AUVs). For the purpose of fish stock assessment, AUVs can be differentiated by a few criteria in particular categories. One of them is detection equipment which can be either hydroacoustic or visual [9-11]. Experimental evidence has shown that video cameras have highly impaired effectiveness in turbid waters, while acoustic cameras are virtually unaffected by turbidity [9]. Acoustic cameras, on the other hand, lack the proper target strength to discriminate individual fish and are largely unable to determine their characteristics [10,11]. Therefore, when identifying species of the observed fish taxa, or their specific characteristics visual cameras provide a much better tool during assessment than their acoustic counterparts [10]. Another difference between two sensors also includes the fact that acoustic cameras use abundance models to assess the size of the biomass, rather than directly counting it [12]. Furthermore, AUVs can be used to observe fish taxa, individual fish or completely different organisms entirely [13-15]. For example, in protected waters archipelago in the Aegean Sea this method has been successfully utilized to identify 27 fish taxa, 21 of which have been categorized at the species level [13]. Along the Atlantic coast of Delaware and Maryland this technique allowed for counting of individual sharks to assess their population quantity, but more importantly, to even track their migration pattern [14]. Moreover, alongside fish, scallop population sizes and densities have also been successfully measured at the sea bottom [15]. While all these methods can be utilized even without the usage of remotely operated vehicles (ROVs) or AUVs, using human divers, applying new technologies removes safety risks, reduces the cost of conducting the operation, saves substantial amount of time and drops the possibility of human error [16]. AUVs have further advantage over ROVs since they have the ability to cover much larger areas and are therefore more suitable for conducting underwater surveys with the only real comparable disadvantage being the fact that the data is not transmitted in real time [17]. AUVs have pre-programmed tracks and are self-navigated using inertial navigation, to be precise, a system consisting of gyro compass, accelerometer, altimeter and other navigation sensors integrated to hold and change a pre-programmed track and in combination with data gathering system, i.e. video and acoustic cameras, can conduct a survey over a chosen area [18]. This allows for the AUV's full autonomy, as the name suggests, and thus longer surveying periods of larger areas. In addition, AUVs can be grouped together and a communication algorithm can be established between using acoustic communication systems, a technology still in development, which allow for better performance and efficacy [19]. Conclusively, AUVs serve as the most optimal platforms for conducting fish stock surveillance which is necessary for assessing the probable magnitude of IUU fishing operations and granting the law enforcement information for conducting further measures.

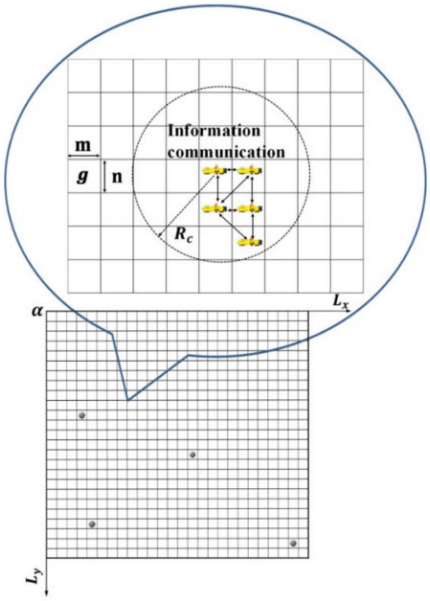

Figure 1 Search area model of multi-AUV system

Source: [19]

2.3. Fish stock assessment using unmanned aerial vehicles

Apart from AUVs, other forms of drone technologies can also be viably applied as an auxiliary system to the main AUV system of surveillance. One such form of drone technology is the usage of unmanned aerial vehicles (UAVs). Unlike the AUVs, UAVs are operated by a person, like the ROV control system, but, unlike it, conducted in aerial rather than maritime plane. Studies have shown that UAVs can indeed be used for abundance assessment [20, 21]. In addition, they can also be used for mapping of the fisheries geographic regions and assessment of the fish habitat [22].

3. OVERVIEW OF EFFECTIVE SEA AREA SURVEILLANCE

While unsustainability of keeping existing fisheries management models soared, sensor improvements opened discussion for broader surveillance applications of UAV in modern, overloaded environment [23, 24]. Their cost-to-benefit ratio surpassed that of traditional manned patrolling platforms [25]. Therefore new, highly autonomous UAV platforms, especially those combining advanced sensors and software become powerful tools for future IUU fishing prevention and catching. This chapter aims to summon development trends, validated scientific ideas and published operational applications of UAVs as a mean of effective sea area surveillance in environment overloaded with challenges [23]. Recommendations for UAV exploitation in the fish abundance assessment is also a valid path [25, 26]. However, although UAVs can be useful for abundance assessment, in this integration model, the role of fish abundance assessment is left to AUVs considering their advantages over UAVs at different depths and weather conditions [27, 28].

3.1. UAV for sea surveillance

Unmanned Aerial Vehicles (UAVs) or simply drones are defined as aircraft without a pilot and controlled from the ground or by a computer program [29]. They can be fixed-winged or rotary-winged. Also, they can further be divided by dimension cost, and the sensors they carry [25, 30]. Due to their and sensor improvements, UAVs pushed the boundaries of efficiency and affordability [31]. That also includes the maritime industry, where AUVs were already used for fauna surveying post-disaster assessment beach maintenance and litter classification platform for photogrammetry search and rescue actions UAVs have also capacity for IUU fishing prevention sea monitoring. Activity has been largely divided into suspecting ships detection, identification, localization, and tracking, and ghost fishing detection and removal [26, 30, 32-35]. According to that UAVs capabilities are:

3.1.1. UAVs for stationary target detection

Research was made on the UAVs detection of crab traps as one of mayor ghost fishing agent [27, 28]. It was stated that remote pilots can detect crab traps using cameras onboard small, non-specialized UAVs. While the detection rate depends on flight altitude, wind and precipitation, transparency of the sea, depth, and trap colour, it can greatly enhance IUU traps detection capability [27, 28]. Nevertheless, although the detection of stationary objects like gillnets and traps is the least complicated task; to make detection truly cost-effective it is necessary to automate it. Something that seems largely overlooked [30].

3.1.2. Trends in UAV fishing monitoring systems deployment

UAVs are very useful for first-view monitoring of a particular sea area and potential IUU fishing ship detection and identification, localization, and tracking [25, 28, 36-39]. Visual image monitoring by UAVs carrying cameras greatly helped Belize's tiny fishery enforcement office Around 10 years ago they started using Solo Quadcopter by company 3DR carrying an onboard camera (few models can be fitted) with live video transmission [40]. At approximately the same time Jamaica led a similar project acquiring two UAVs one of which is X8 Skywalker [41]. Not long after that Jamaican official announced the procurement of new UAVs with greater reach [42]. In 2023. testing flights were conducted in French Guiana consisting of patrolling over an area of more than 70km in a radius with French-made long-range fixed-wing UAV BOREAL produced by French company BOREAL SAS [43]. Most recently, Palau has announced the acquisition of an advanced Matrice 350 RTK UAV for IUU fishing combating [44]. Chinese province of Zhejiang also started using long-range UAVs for combating IUU fishing a few years ago. Their JOUAV CW-25E with a powerful camera enhanced with computer vision software can automatically track and identify IUU fishing ships [45]. Systematic list of mentioned UAV systems is provided in the Table 1 below.

Table 1 UAVs for Maritime Surveillance

Model	Country	Producer	Type	Start of Deployment	Range	Max horizontal speed	Endurance	Sensors and software	Cost*
Scan Eagle-USCG 2017	USA	Boeing-Insitu	Fixed wing, heavy fuel or gasoline engine	2013.	60 NM	80 knots	Up to 18 h	EO telescope (high zoom day FMV), MWIR/EO dual sensor, ViDAR (maritime surface search)	Not announced officially Can be estimated to 1.4 million* (2023.-hole system)
SKYWALKER X8	Jamaica	UAV Model	Electric powered fixed wing	2015.	Up to 10 km	65-70km/h	25 min	Without frame, but carries up to 2kg	150-400
Solo Quadcopter	Belize	3DR	Small rotary-winged, quadcopter	2016.	800 m	55 mph	15-25 min*	Built-in GoPro frame, gimbal stabilised	800(2019)
TEKEVER AR5- EMSA	EU	CLS-TEKEVER consortium	medium-altitude, medium-endurance fixed-wing UAS	2021.	Up to 1000 km	100 km/h	Up to 9h	EO/IR cameras, AIS sensor, EPIRB, Satcom terminal, Maritime Radar, radar emitter detector, Mobile phone detector	Not announced officially
DJI Mavic Enterprise	Seychelles	DJI	Electric powered fixed wing	2021.-2022.	9-15 km	15 m/s	45 min	4/3 CMOS Wide Camera, 56× Hybrid Zoom, 640 × 512 px Thermal Camera, AI enhanced	3500 (2021.)
BOREAL ISR	France	BOREAL SAS	long-range, fixed wing drone	2022.	800 km	37-70 knots	Up to 8 h	E/O HD (IR) sensors, AI enhanced 360° day/night vision gimbal camera	Not announced officially
JOUAV CW-25E	China	JOUAV Unmanned Aircraft System	Long Endurance Electric Fixed-wing VTOL Drone	2023.	35-100 km	72 km/h	4 h	AI enhanced MG-150E gimbal camera	Not announced officially
AEROSONDE 4.7	Australia	Aerosonde Uncrewed Aircraft System	Hybrid Quadrotor,vertical takeoff and landing (VTOL) drone	2024.	140 km (75 NM)	45-65 kt	Up to 12	Full-Motion Video (FMV), Maritime Wide Area Search Synthetic Aperture Radar (SAR) Automatic Identification Systems (AIS), Light Detection and Ranging (LiDAR)	$25,610,000 (whole system-2022.)
Matrice 350 RTK	Palau	DJI	Small rotary-winged, quadcopter	2025.	8-20 km	23 m/s	Up to 55 min	-Directional Positioning, Night-Vision FPV Camera Night-Vision, Multi-Payload Support	From 13 789 €

*Cost is somewhere expressed for the sole drone and where it was possible for system as a hole.
Sources: [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66]

3.1.3. Spatial organization of UAV area surveillance

It is evident that although UAVs equipped with cameras can be very effective and affordable tools in expanding situational awareness and broadening areas of surveillance, their surveillance role can be greatly enhanced by combining their sensors with ground process centres where more powerful software can be employed. That ground station can be on cost guard ships, so they have even greater reach [67]. One ground station can, with raising automatization, launch big number of drones using swarm control, as described in [36]. Such an integrated system can take area surveillance and IUU fishing catching to another level. Moreover, number of

UAV systems employed, positioning of the ground station and size and shape of area they survey or protect can impact surveillance effectiveness. For that reason, different positioning rules have been proposed for ground station in accordance with size and shape of marine protected area and number of UAVs available that can be seen in Fig. 2,3 [36].

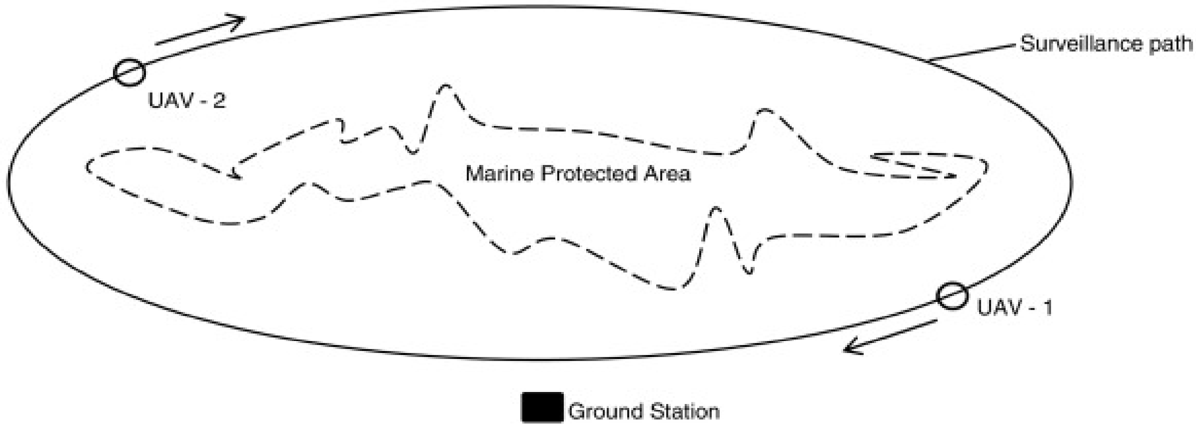

Figure 2 Elliptical planning of marine protected area surveillance

Source: [36]

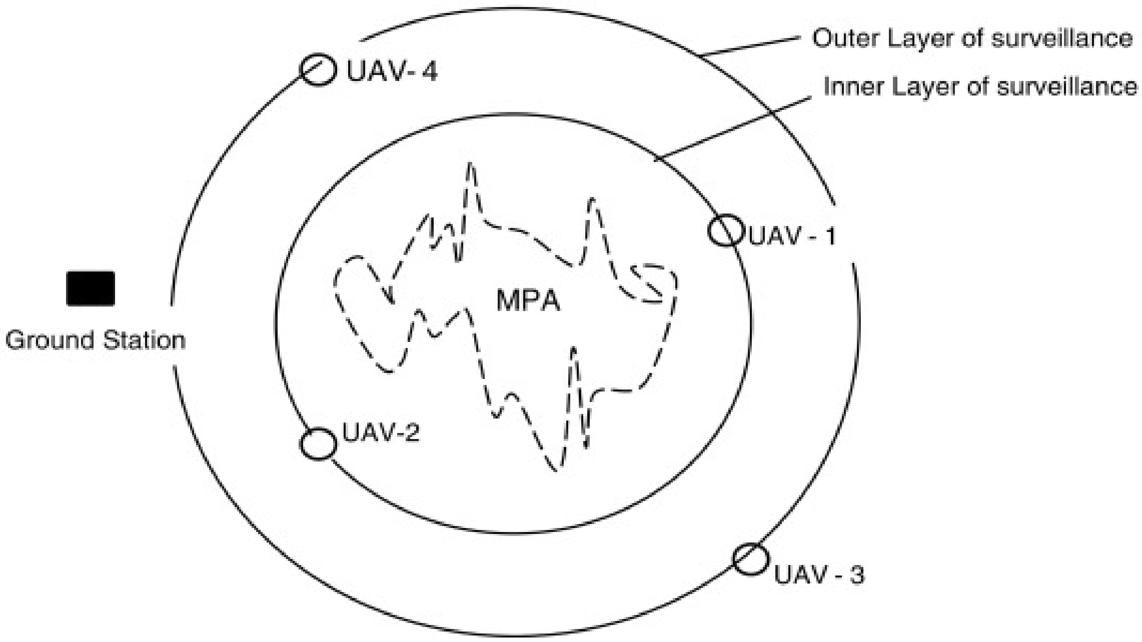

Figure 3 Circular planning of marine protected area surveillance

Source: [36]

4. PROPOSED INTEGRATION MODEL OF AUV AND UAV SYSTEMS AND ALERT THRESHOLD BASED ALGORITHM FOR COMBATING IUU FISHING

In previous chapters AUV and UAV fish stock assessment and catching methods have been discussed. Although UAVs with computer-enhanced photographic capabilities can be used directly, in patrol-like inspections, it might be more economically viable to hold them in passive rest until the proposed threshold-based algorithm raises an alert over a specific area based on fish stock reduction. It will also make concentration of UAVs extensive only over the areas where stock depletion has been detected, thus further optimizing the resource allocation as well as raising the probability and reducing the time needed to catch the IUU fishing vessels. This chapter will provide the necessary information about proposed model and algorithm.

4.1. Static and dynamic threshold algorithms

When discussing threshold-based algorithms, there are two types of such algorithms, namely static and dynamic algorithms. Static threshold algorithms use a constant value as a threshold, while dynamic threshold algorithms use a variable value [68]. Thus, dynamic threshold algorithms are more complex, however, as alert threshold alert algorithm is dependent on different fish species, geographical area and seasonal and periodical changes, so does the threshold vary based on these parameters, making it a dynamic one.

4.2. Maximum sustainable yield

In the first chapter of this paper, a thorough analysis of the monitoring of change in fishing activity through the assessment of fish stock has been presented. Accordingly, an increase or decrease in catch is calculated, however, stationary catch does not necessarily mean sustainability in the long run, nor does an increase in catch necessarily mean an inherent lack of it. Threshold for this algorithm therefore can not be taking the catch of the previous year as a maximum. Hence, maximum sustainable yield is introduced. As fish populations increase following the logistics curve or the "S" curve, since at first there is too little biomass to reproduce quickly, then it starts reproducing exponentially after a while and in the end, it hits the limit presupposed by the environment [69, 70]. The change of fish population over time can thus be described as the first derivative of the "S" curve and be expressed as:

$$\frac{dB}{dt} = \frac{rB_1 - B}{B_0 - pB}, \quad (3)$$

where $\frac{dB}{dt}$ is the change of biomass over time, r is the exponential growth factor, B_1 is the initial biomass, B_0 is the intersect and the stationary point of the population growth curve and p is the decline factor [49]. If plotted, the change in growth rate curve will resemble a pseudo-parabola as in Fig. 4:

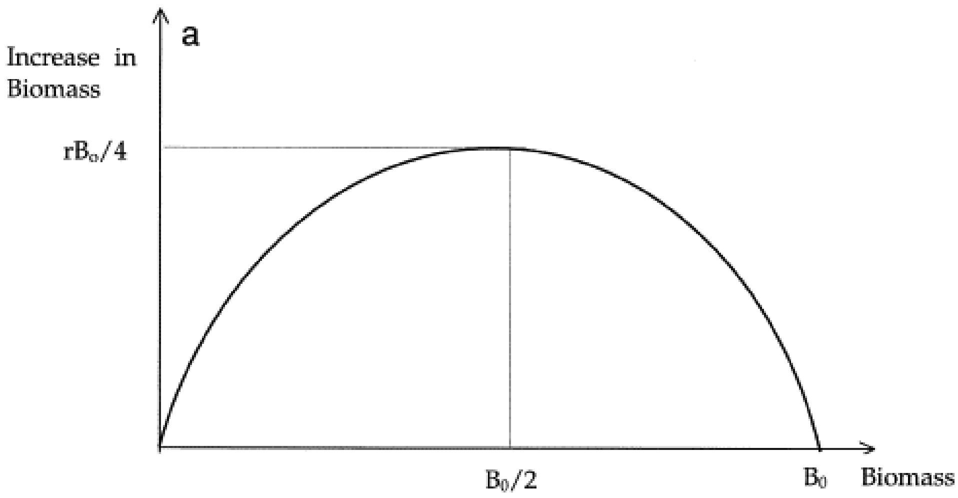

Figure 4 Change of growth rate of fish population

Source: [70]

From this relationship, it is apparent that biomass of the maximum sustainable yield, which is the maximal quantity of extracted biomass which will not cause the decrease in fish growth rate, is position at the maximum of the growth rate change curve and can be expressed as [71]:

$$B_{msy} = 0.5B_0, \quad (4)$$

to precisely calculate the maximum sustainable yield, statistical data of fish population over periods of time need to be collected and examined. Once obtained, the maximum sustainable yield can be used as a threshold for allowed and prescribed catch quantity and, consequently, a threshold for alarm after which UAV catching methods can be employed in order to combat IUU fishing activities.

4.3. UAV catching system's threshold alert algorithm

As expressed previously, in order to maximize the effectiveness of UAV catching by increasing their concentration in the areas with high alarm for biomass decrease due to IUU fishing and to optimize the resource allocation, maximum sustainable yield is used as a reference point and data collected by combined AUV and UAV fish stock surveillance is used as an input data for comparison with the reference point. Furthermore, if the fish mortality due to fishing does not increase above maximum sustainable yield no measures need to be taken and UAV systems for catching IUU fishing vessels can be held in passive, thus saving the resources and optimizing their allocation. Therefore, the final explanation of algorithm is as follows: AUV and UAV surveillance platforms collect data on fish stock; maximum sustainable yield is calculated; from data collected, catch quantity is calculated; catch quantity is compared to maximum sustainable yield; if the catch is smaller or equal to yield, no measures ought to be taken and UAV systems for catching IUU boats can stay at passive; if the catch is greater, UAV systems are activated over the alarmed area and help combat the IUU fishing. The algorithm is further described in Fig.5:

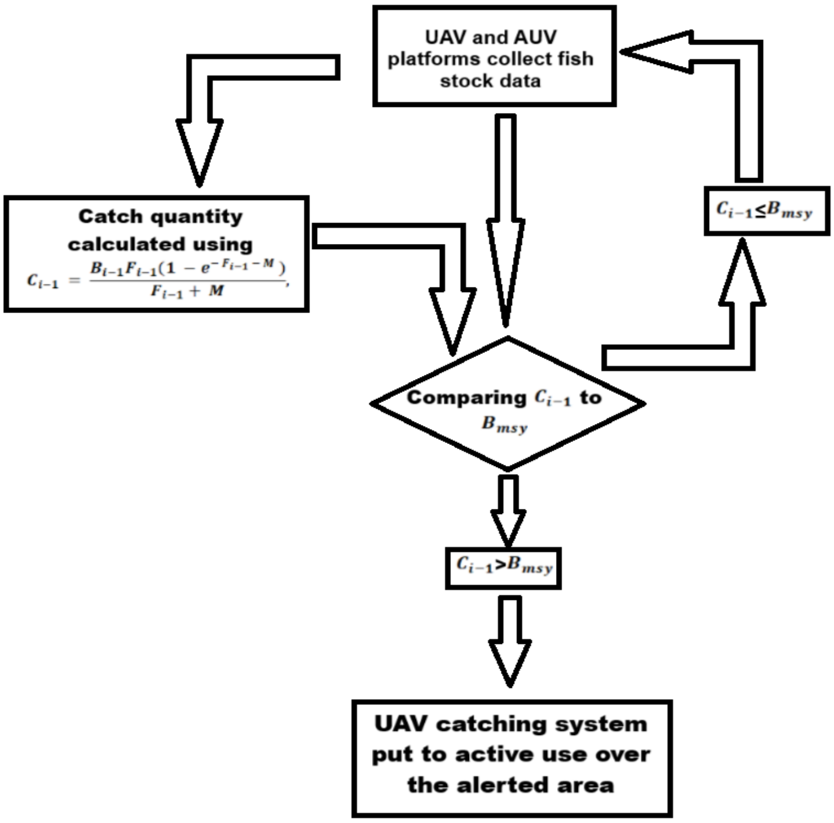

Figure 5 UAV catching system's threshold alert algorithm

Source: Authors' original work

5. CONCLUSION

To conclude, this paper has thoroughly examined the interconnected nature of fish stock depletion and the prevalence of IUU fishing activities. Through a multifaceted analysis, it has become evident that combating IUU fishing requires not only stricter enforcement mechanisms but also the integration of advanced technologies for monitoring, assessment, and intervention. The research has proposed a comprehensive framework that utilizes AUVs and UAVs for both fish stock abundance estimation and real-time surveillance of suspicious maritime activity. This dual use of autonomous platforms not only enhances operational efficiency but also minimizes human risk and cost. A central feature of the proposed model is a threshold-based algorithm that leverages periodically gathered fish stock data to determine optimal points for activating IUU intervention protocols. By deploying UAVs in swarm configurations only when certain ecological thresholds are breached, the system aims to concentrate resources in critical areas while avoiding unnecessary expenditures in regions with stable stock levels. This data-driven approach promises to increase the responsiveness and cost-efficiency of enforcement actions. However, the algorithm's effectiveness is contingent upon the accuracy and timeliness of ecological data. Its periodic nature may delay action in fast-developing IUU scenarios, making it more suitable for addressing systematic or long-term exploitation patterns rather than urgent, short-term incidents. Furthermore, while the model assumes that a significant portion of fish stock decline is due to fishing pressure, it currently does not account for alternative mortality factors such as climate change-induced stress, pollution, disease outbreaks, or the introduction of invasive predatory species. This assumption could lead to misinterpretation of fish stock signals and potentially misguide the system's response if not cross-referenced with broader ecological datasets. In parallel, the paper has explored the emerging role of advanced sensory technologies in enhancing IUU detection capabilities. Recent advancements in computer vision and multisensory data fusion have enabled real-time vessel detection, localization, and identification. These systems have proven effective in identifying vessels based on visual cues such as hull shape, movement patterns, and even hull plate matching. Some researchers have successfully integrated dual-stage recognition systems that combine fast but less precise onboard detection with slower, high-accuracy processing on the ground. Nevertheless, these technological solutions are not without their limitations. Many systems still rely heavily on AIS (Automatic Identification System) data, which can be disabled by IUU vessels to evade detection. Hull plate recognition, while promising, depends on a robust and up-to-date database, and its effectiveness is reduced when dealing with unregistered or foreign vessels operating outside recognized standards. Additionally, environmental conditions such as fog, high seas, and poor lighting can impair sensor accuracy, while legal and jurisdictional constraints may limit enforcement capabilities in certain maritime zones. Looking ahead, the development of an effective IUU combating system must be seen as an evolving process—one that continually incorporates emerging scientific discoveries and technological innovations. It is crucial to adopt a modular, flexible architecture that allows integration of new detection tools, data sources, and intervention strategies as they become available. At the same time, every new solution must be evaluated not only for its technical capabilities but also for its economic viability, operational resilience, and legal compatibility across different regions and maritime frameworks. In summary, the future of sustainable marine resource management lies in the smart convergence of autonomous monitoring platforms, artificial intelligence, and ecological modelling. By adopting a holistic, adaptive, and data-informed approach, we can build a more robust and responsive system that not only deters IUU fishing but also ensures long-term preservation of marine ecosystems while maximizing the efficiency of resource utilization.

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SITUATIONAL AWARENESS AMONG SEAFARERS IN CONDITIONS OF INFORMATION OVERLOAD ON THE NAVIGATIONAL BRIDGE

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Abstract

In modern maritime navigation, the sensor systems, electronic charts, navigation systems, integrated systems, and automated alerts have significantly increased the volume and complexity of information presented to bridge officers. While these technologies aim to enhance operational awareness, they can also lead to cognitive overload, contributing to reduced situational awareness (SA) and increased risk of human error. This research explores the theoretical relationship between information overload and SA among seafarers operating conventional vessels. The study aims to construct a theoretical framework grounded in human factors and cognitive psychology. Key parameters such as perception of situation, attention narrowing, and decision fatigue are investigated in the context of bridge operations. Bayesian Belief Networks (BBNs) are designed to represent the probabilistic dependencies between workload, information density, cognitive state, and decision-making. This model will serve future simulation-based validation, such as reaction time and alarm response accuracy. This paper will provide information for training and workload management.

Keywords: situational awareness, human error, bridge operations

1. INTRODUCTION

Situational awareness in domains like aviation, healthcare, and military operations has been extensively studied, with a consensus emerging on its importance for safety-critical decision-making. Situational awareness is also very important in maritime domain and it has lots of infuence on maritime accidents.

Situation awareness (SA) refers to the perception of environmental elements within a specific volume of time and space, understanding their meaning, and projecting their near future status. It refers to the ability to perceive, understand, and predict the environment in which an individual operates. [1]

Definition of situation awareness is that it is a ability of an individual to possess a mental model of what is going on at any one time and also to make projections as to how the situation will develop. [2]

In high-stress domains such as maritime navigation, officers must manage vast amounts of information to make timely and accurate decisions. However, information overload can diminish an officer's situational awareness, leading to impaired decision-making and increased risk of accidents.

Information overload occurs when the volume of information exceeds the capacity of the human operator, affecting their ability to focus on critical data Information overload on the navigation bridge can be influenced by the number of alarms, visual distraction or decision making in complex navigation situations (heavy traffic, complex coastal navigation, ice…). In these situations, situational awareness includes the Officer on watch understanding of the situation as a whole and forms a basis for decision-making. [3] Empirical studies show that information overload is related to burnout, stress, anxiety [4][5][6] and various psychological symptoms [7] and has a negative impact on job satisfaction [8]

Information overload is associated with severe performance degradation, especially in the context of disruptions and interruptions [9] Finally, studies show that the quality of individuals' decisions is affected by information overload. [10]

The officer on watch must integrate data from various sources such as ECDIS, radar, Doppler log, echo sounder, AIS, Navtex, visual detection, and alarms (target lost, safety contour...).

A high cognitive load from these devices and systems can lead to information overload, which can affect situational awareness and put the vessel in unwanted situations.

Navigation systems and their use are increasing and the systems are becoming more complex. The purpose of navigation bridge systems is to make navigation safer, but the problem arises when the human brain starts to make mistakes due to information overload. Trying to find the limit of information that causes officers to make poor navigational decisions and reduce situational awareness is very difficult and highly individualised. Focus of the paper is to investigate how increasing data load (bridge informations and environmental information) significantly degrade the situational awareness of Officers on watch, resulting in delayed or wrong navigational decisions. Aim of paper is to detect what amount of information influences poor decision-making among seafarers.

Over the past years, several maritime accidents have underscored the critical role of information overload and mismanagement in compromising safety on the navigational bridge. These incidents highlight the complex interplay between human factors, system design, and operational protocols. Studies show that for each serious accident in the maritime domain, or in any other domain, there are a larger number of incidents, an even larger number of near-misses, and many more safety-critical events and unsafe acts. [11]

In October 2023, two cargo ships collided near Heligoland, Germany, resulting in multiple fatalities. The investigation revealed that the bridge teams of both vessels failed to effectively communicate and assess the situation, leading to a catastrophic collision. The Marine Accident Investigation Branch (MAIB) noted that the crew's inability to process and act upon critical navigational information contributed significantly to the incident. [12] It is important to point that for this special case Investigation is is not yet completed and only an interim repot has been issued, with no accident causes indetifed

The Ever Forward grounding (2022) revealed that distraction and lack of situational awareness on the part of the pilot, along with passive bridge management, led to the vessel missing a key turn [13]

On January 7, 2021, the bulk carrier Ocean Princess struck an oil and gas production platform in the Gulf of Mexico. The National Transportation Safety Board (NTSB) attributed the incident to fatigue, distraction, and over-reliance on Electronic Chart Display and Information System (ECDIS), resulting in a charting error and poor bridge resource management. [14]

Norwegian frigate KNM Helge Ingstad collided with the tanker Sola in on 8 November 2018 outside the Sture Terminal in the Hjeltefjord in Hordaland county at about 04:00 local time (03:00 GMT) as the frigate, part of Nato's fleet, was sailing inner fjords for training. All 137 of its crew from Nowegian frigate were evacuated and eight people were injured. The Accident Investigation Board Norway (AIBN) investigation has shown that the situation in the Hjeltefjord was made possible by a number of operational, technical, organisational and systemic factors. The frigate's Automatic Identification System (AIS) was set to passive mode (invisible to other vessels). The bridge crew failed to adequately interpret radar data and communicate effectively, leading to the collision.[15] The *KNM Helge Ingstad* frigate collision (2018) occurred partly due to AIS being set to passive, preventing other vessels from detecting the ship, combined with poor bridge communication. [16] This collision was attributed to multiple factors, including information overload.

Collision between ro-ro passenger ferry Red Falcon and moored yacht Greylag from 21 October 2018 happend when Red Falcon navigating in severely reduced visibility in Isle of Wight. According to investigation from The Marine Accident Investigation Branch (MAIB) the Master became fixated upon the information displayed on his electronic chart and operating engine controls, ignored information displayed on other electronic equipment, and became cognitively overloaded due to high stress leading to a failure in maintaining situational awareness. [17]

At around 8:50 a.m. on April 16, 2014, the Sewol ferry on route from Incheon to Jeju, capsized off the southwestern island of Jindo, South Jeolla Province, after making rapid turns in the Maenggol Channel, which is known for its strong currents. Result was loss of over 300 lives. Investigations revealed that sinking of MV *Sewol* was a combined result produced by the steering error, lessened restoring force caused by overloading and crew's inability to prioritize critical data. Cause of accident is a mixture of a rapid course changes and poor bridge team coordination [18]

Allision of containership M/V Cosco Busan with the Delta Tower of the San Francisco Oakland Bay Bridge, San Francisco, California, November 7, 2007 caused oil spin. No injuries or fatalities resulted from the accident, but the fuel spill contaminated about 26 miles of shoreline, killed more than 2,500 birds of about 50 species, temporarily closed a fishery on the bay, and delayed the start of the crab-fishing season. Total monetary damages were estimated to be $2.1 million for the ship, $1.5 million for the bridge, and more than $70 million for environmental cleanup.The Cosco Busan pilot, at the time of the allision, experienced reduced cognitive function that affected his ability to interpret data and that degraded his ability to safely pilot the ship under the prevailing conditions, as evidenced by a number of navigational errors that he committed. [19]

These cases demonstrate that even when systems are operational, human error due to information overload and poor resource management can result in serious accidents. Information overload, whether due to excessive communication, over-reliance on technology, or poor team coordination, can significantly impair decision-making and situational awareness on the bridge. All cases demonstrate common factors which include excessive or poorly prioritized information, failure to respond to alerts, lack of coordination among the bridge crew, and insufficient use of navigational tools. Alarm saturation, multitasking, and unclear roles often contribute to degraded performance.

2. MODEL AND DATA

It is generally advisable to use tools and procedures that have been developed for the purpose of risk assessment and have proven their value in practice for this purpose, as demonstrated by company references or practical examples.[20] Weakness in bridge organization and management has been cited as a major cause for marine casualties worldwide. Accidents in operations are frequently caused by resource management errors. [21]

To be able to understand the most influential factors that could lead to an information situation Bayesian Network is used to investigate how information overload influences situational awareness. Using Bayesian modeling, it is also possible to identify the most significant contributing factors to information overload in the maritime navigation context. The BN's structure is based on expert knowledge and prior studies on cognitive overload and human factors in high-stress environments. [22] Bayesian Networks have been employed across various domains to model uncertainty and dependencies between variables. Bayesian network is great tool for risk assesment, also in a maritime domain, helping understand relations between most influencing variables for decision-making and navigation system failures.

Table 1. presents influencing factors for information overload and situational awareness

Table 1 Definition of variables used for Situational Awareness Bayes network

Alarm Load	Frequency of alarms received by the officer. Represents the load of alarms triggered by navigational systems (e.g., radar, sonar). High alarm load could overwhelm the officer's attention.
Visual Clutter	The level of visual information and distractions. Refers to the amount of clutter or unnecessary information displayed on navigational screens (e.g., radar, sonar, maps). Excessive visual clutter can impair decision-making.
Task Complexity	The complexity of tasks the officer needs to perform. Refers to the complexity of the tasks the officer must perform, such as navigation, collision avoidance, and responding to changing conditions.
Traffic Density	The density of traffic around the ship. Refers to the level of maritime traffic in the officer's environment. High traffic density can increase workload and cognitive load.
Fatigue Level	The officer’s level of fatigue. Represents the officer's level of fatigue, which impacts cognitive performance and decision-making ability
System Reliability	The reliability of onboard systems. Represents the reliability and accuracy of the ship's systems, such as radar, sonar, and GPS. System failures increase the officer’s workload.

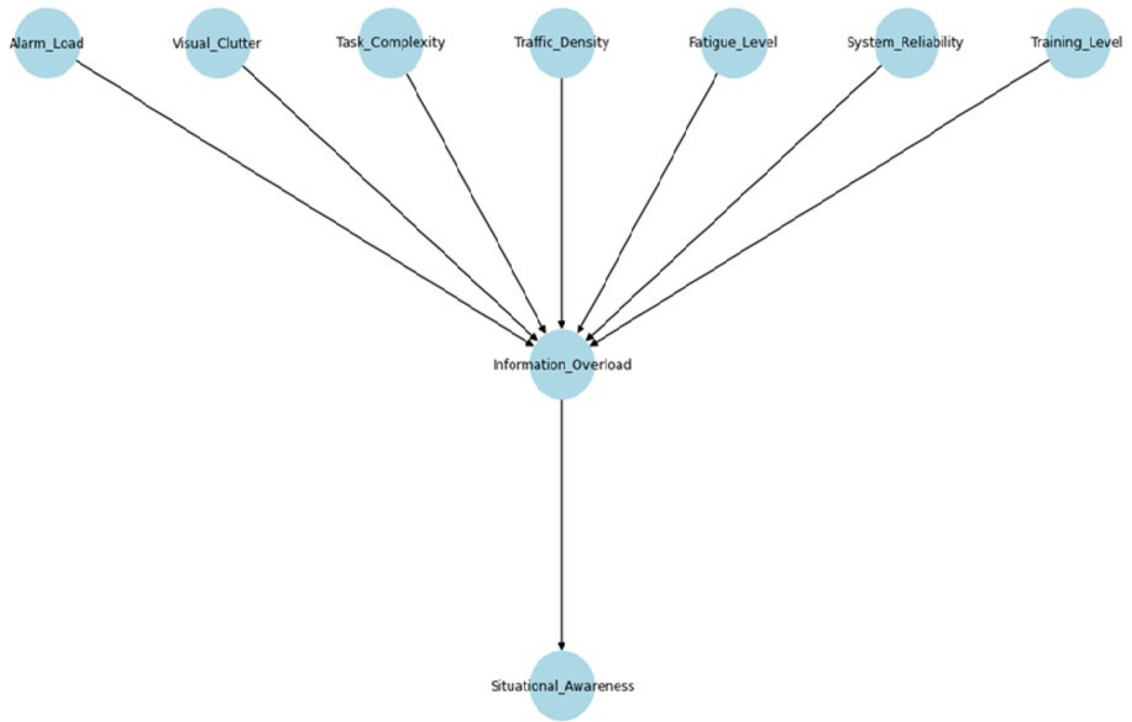

Figure 1 Situational Awareness Bayes Network

System reliability and Task complexity all contribute to Information overload. High levels of any of these factors can increase the likelihood that the officer will experience information overload.

Information overload acts as a mediator between these various factors and Situational awareness. As overload increases, the officer's ability to maintain situational awareness decreases. High information overload decreases situational awareness, making it harder for the officer to make sound decisions.

Situational awareness is the end result of the complex interaction between information overload and various influencing factors, and is crucial for safe navigation. High situational awareness enables the officer to make accurate, timely decisions. However, as information overload increases, situational awareness tends to decrease. Situational awareness directly impacts the officer's ability to navigate the ship safely, recognize threats, and respond to potential hazards.

To identify the most influential factors on Information overload, a sensitivity analysis was performed. Sensitivity analysis is technique that can help validate the probability parameters of a Bayesian network. This is done by investigating the effect of small changes in the model's numerical parameters (i.e., prior and conditional probabilities) on the output parameters (e.g., posterior probabilities). Highly sensitive parameters affect the reasoning results more significantly. Identifying them allows for a directed allocation of effort in order to obtain accurate results of a Bayesian network model. In model data for variables are syntetic generated based on literature and data is subject to change according to situations and the environment

Table 2 Conditional table of probability for each node

	YES	NO
Alarm Load	0,5	0,5
Visual Clutter	0,6	0,4
Task Complexity	0,5	0,5
Traffic Density	0,4	0,6
Fatigue Level	0,7	0,3
System Reliability	0,2	0,8

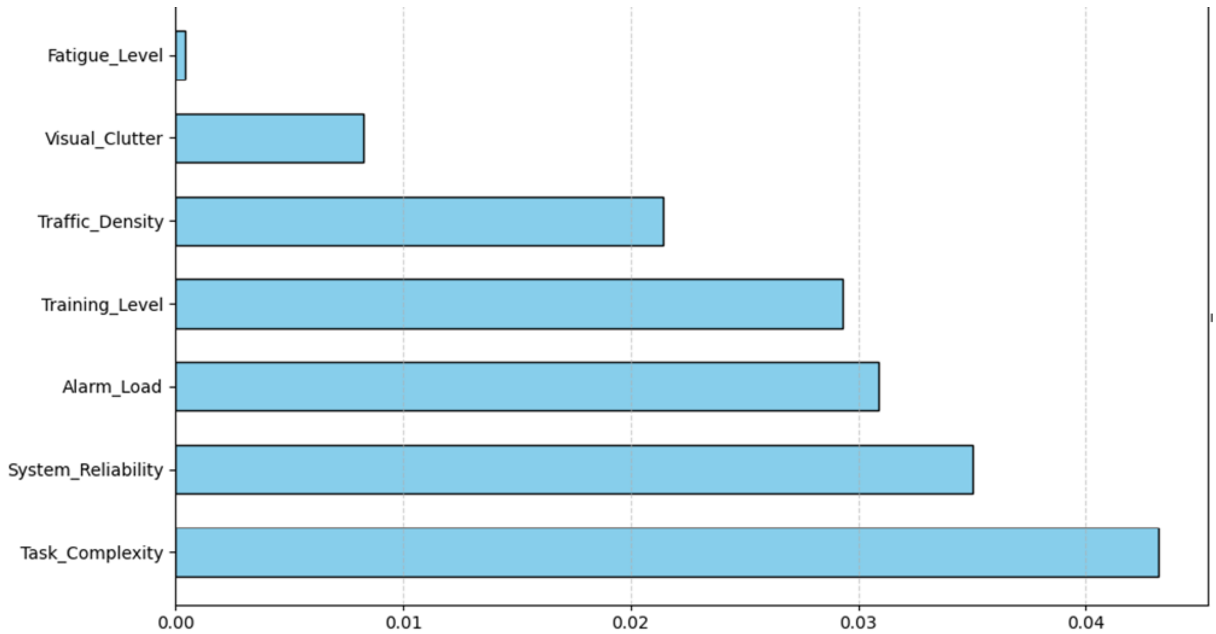

Figure 2 Tornado diagram for Information Overload

A Tornado diagram was made to represent the Sensitivity analysis of Information Overload and Situational Awareness. It is presented that Task Complexity is the most impactful factor, followed by System Reliability and Alarm Load.

Table 3 Results of Tornado diagram

Rank	Variable	ΔP(Information_Overload = 1)
1	Task_Complexity	0.0432
2	System_Reliability	0.0350
3	Alarm_Load	0.0309
4	Training_Level	0.0293
5	Traffic_Density	0.0214
6	Visual_Clutter	0.0082
7	Fatigue_Level	0.0004

3. RESULTS

The Sensitivity analysis and Tornado diagram reveal that Task complexity is the most influential factor contributing to Information overload. This suggests that simplifying the tasks or breaking them into smaller, manageable components could help reduce the cognitive load on the officer, thereby improving situational awareness. Complex tasks require officers to divide attention across multiple systems, analyze dense information, and make time-critical decisions. In high complexity scenarios such as maneuvering in restricted waters or responding to simultaneous alarms cognitive resources become stretched. This directly increases the likelihood of Information overload, reducing the officer's ability to process incoming data effectively. The result supports previous literature emphasizing the role of task design and automation in cognitive load management.

Visual clutter and Fatigue level also play significant roles, indicating the importance of minimizing distractions on the bridge and ensuring officers are well-rested to maintain optimal Situational awareness.

Visual clutter has a surprisingly low standalone impact on Information overload. This may indicate improved bridge design and screen ergonomics in modern vessels, or officers' growing ability to filter visual noise. However, clutter can still act as a cumulative stressor, especially when paired with fatigue or multiple alarms. Thus, while low on the sensitivity scale, its interactive effects should not be ignored.

Contrary to common assumptions, Fatigue level is presented as the lowest direct impact on Information overload in model. This does not mean fatigue is unimportant. The influence of fatigue is indirect and culumative, manifesting through slower processing, poorer judgment, and wrong decision-making. Fatigue influences other variables, and in this model it is put as a moderating variable rather than a direct contributor.

Very strong influencing variable is Traffic density and it has very high contribution to information overload. High traffic density in navigation demands continuous tracking using visual monitoring or radar detection, communication, and course corrections. This procedures generate constant information flow and lots of real time decison making. High density in combination with poor visibilty or equipment failure can have really strong inpact to information overload

Task complexity has the big infulence on Information overload. Officers on watch are required to monitor navigation systems and alarm systems, analyze information, and make time-critical decisions. In high-complexity scenarios such as maneuvering in restricted waters, channels, hight density traffic waters and responding to simultaneous alarms cognitive resources become demanding. This directly increases the likelihood of Information overload, reducing the officer's ability to process incoming data effectively.

System reliability variable is second strongest influencing variable in presented model. Meaning that even small system malfunction of radar, GPS, AIS, ECDIS or other navigation support systems or devices makes big influence in decision making of Officer. Low reliability in navigation systems forces manual verification and cross-checking between navigation systems used on navigational bridge and it leads to information overload. The conclusion is that the reliability of navigation systems contributes to the reduction of information overload.

Excessive or poorly prioritized alarms generate high levels of stress and decision paralysis, known as "alarm fatigue". An increased Alarm load contributes directly to Information overload, as it forces the officer to triage alarms some potentially false or redundant while navigating complex environments. Our model confirms that effective alarm management systems can significantly reduce overload and its downstream consequences on situational awareness.

Although Training level is not an environmental or system factor, its influence is noteworthy. Well-trained officers likely possess cognitive schemas to filter noise, prioritize cues, and quickly interpret system outputs. Therefore, high training levels mitigate the impact of other overload contributors. This finding reinforces the importance of advanced training protocols that simulate overload conditions, enabling better preparation for real-world challenges.

This study underscores the need for careful attention to human factors when designing navigational systems and operational protocols. By minimizing Information overload, we can enhance situational awareness and improve the safety and efficiency of maritime operations. Training programs should emphasize how to manage Task complexity and reduce unnecessary Visual clutter.

Recently developed concept of distributed situation awareness, which takes a systems perspective on the concept and moves the focus on situation awareness out of the heads of individual operators and on to the overall joint cognitive system consisting of human and technological agents. Situation awareness is viewed as an emergent property of collaborative systems, something that resides in the interaction between elements of the system and not in the heads of individual operators working in that system. [25]

4. CONCLUSION

The paper demonstrates the utility of Bayesian Networks in modeling complex, uncertain relationships in high-stress environments like maritime navigation. The results emphasize the importance of reducing information overload to improve situational awareness. The findings can be used to guide the development of more effective training programs, system designs, and operational protocols for bridge officers. Future work needs to be the use of real data to validate the model. Using actual data from bridge operations to validate the BN model and refine the conditional probability distributions. Including additional factors such as environmental conditions (e.g., weather) and system failures to create a more comprehensive model. Implementing the BN for real-time decision support on the bridge to enhance situational awareness during critical moments.

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THE DECARBONIZATION OF SEAPORTS: AN OVERVIEW OF SELECTED MEASURES

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Abstract

Ports are considered critical infrastructure as they play an important role in international trade and overall economic growth. There are around 4,000 ports worldwide, of which around 1,200 are located in Europe alone. Ports around the world face the same challenge of providing competitive services while ensuring that the negative impact on the environment is minimized, with the environmental problem being particularly acute in peri-urban ports. While the majority of maritime transport emissions are generated during shipping, ships' auxiliary engines run during port calls to keep the ship's systems running. Ships in port usually contribute more than half of all port-related emissions. The remaining emissions come from the port itself. The aim is to reduce port emissions by 90% by 2050. Ports are already working hard to reduce their environmental footprint and gain the support of local communities. They are applying a combination of soft and hard measures, such as reduced charges for greener ships or a truck arrival booking system and other digitalization approaches, as well as offering alternative fuels for ships and shore power (cold ironing), purchasing sustainable cargo handling and other terminal equipment, using renewable energy sources, developing electrical micro grids, etc. These measures represent a major financial, infrastructural and operational challenge, at least initially. This paper presents measures (examples of best practices) that ports have implemented to achieve cleaner operations with an indication of the cost of implementation.

Keywords: seaport, decarbonization, electrification, renewable sources, cost

1. INTRODUCTION

Maritime transport is considered the most energy-efficient and environmentally friendly mode of transporting large quantities of cargo. It is of crucial importance for world trade, with around 12 billion tons of cargo transported over sea annually. However, without remedial actions, maritime transport emissions could increase by 130% by 2050 compared to 2008 levels [1]. On the other hand, International Maritime Organization (IMO) wants to achieve net zero carbon dioxide (CO2) emissions from maritime activities by 2050 with 40%

reduction by 2030 and 70% by 2040 compared to 2008 baseline levels [2]. The aim is to reduce also port emissions by 90% by 2050 [3].

Ports play a vital role in economic and social development for the regions they are in, which is evident through above-average employment rates and wages, higher-than-average net migration and motorization levels etc [4]. At the same time, ports pose environmental and human well-being challenges from three primary sources: port operations, ships calling to the port, and the traffic in the port's proximity [5]; in average ships account for around 60% of port emissions, around 30% of emissions come from land transport and remaining around 10% from the terminals [6]. Besides climate changing emissions, ships also emit local pollutants such as sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter (PM), which can affect human health. In fact, emissions from shipping are leading to around 265,000 premature deaths worldwide every year on the other [7].

Ports are adopting green initiatives to foster an environmentally friendly development while still ensuring safe and efficient operations [8]. In recent years, they are getting more engaged in decarbonization of the maritime sector as a whole [9]. The concept of decarbonization in the maritime sector extends beyond the CO2 or greenhouse gas (GHG) emissions. It encompasses the mitigation of a broader spectrum of pollutants, including above mentioned NOx, SOx, as well as other harmful emissions ([10]; [11]). Achieving decarbonization in shipping is a complex and time-consuming process that necessitates changes in technology and operational practices ([12]; [13]). The process of decarbonization is impeded by a range of economic barriers (e.g limited access to capital, high implementation and hidden costs) as well as non-economic challenges (e.g. policy and technical issues). These difficulties are further emphasized by the sector's international nature and the involvement of a large array of stakeholders [14].

The aim of the paper is to present the economic aspect of several operational and technological measures that ports can take to decarbonize their operations. These measures are given an approximate cost and timeframe for implementation.

The paper is structured into four chapters. The introductory chapter presents the problematics addressed in the paper. A short description of methodology applied is described in the second chapter. The third chapter is the core chapter of the paper delivering a literature overview on the port decarbonization measure. Conclusions are given in the fourth chapter.

2. METHODOLOGY

The literature review was done by searching the Science Direct database with the following syntaxes: "("decarbonization of ports" or "port greening" or "port decarbonization") and "cost"" and "("on shore power supply" or "cold ironing" or "electrification" or "renewable energy" or "alternative fuels") and "cost" and "port"". After removing duplicates and irrelevant papers, the core corpus of 133 contributions remained for the analysis. The focus was given to more recent publications. During the analysis additional relevant papers, reports and web sites emerged which helped to comprehensively address the research question: What are current measures to decarbonize seaports and at what price they come?

VosViewer was used to present the most frequently used words in the analyzed corpus of 133 contributions, mostly scientific papers and book chapters. After applying the thesaurus to combine similar keywords into a single keyword, 18 keywords with at least five occurrences emerged as can be seen in Figure 1. These keywords were divided into five clusters. The VosViewer visualization presents a network of interconnected terms related to green ports, decarbonization and shipping, organized into color-coded clusters.

The blue cluster centralizes around the term decarbonization. This cluster emphasizes strategies and technologies aimed at reducing carbon emissions in maritime operations (wider than ports). Red cluster is about green ports and sustainability. It focuses on port-level initiatives to enhance environmental performance and integrate clean energy solutions. The green cluster addresses the broader environmental impact of shipping and explores alternative fuels and emission reduction strategies. The yellow cluster focuses on clean fuel innovations for maritime applications both for shipping and ports. The purple cluster is linked to multiple clusters and represents the overarching shift from fossil fuels to sustainable energy sources, bridging various aspects of maritime and port decarbonization.

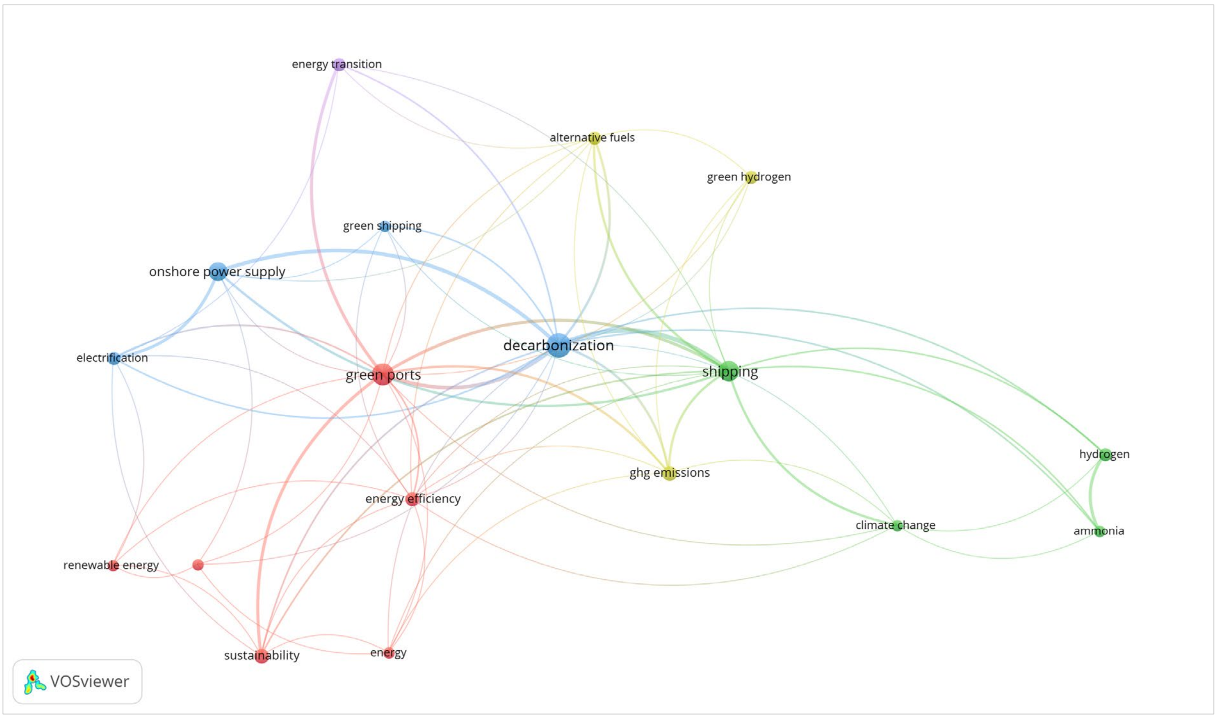

Figure 1 The co-occurrence of keywords in literature corpus

Source: Authors

3. DECARBONIZATION OF SEAPORTS

Maritime transport consumes large amounts of energy; in fact, the energy demand of international shipping (including ports), increased on average by 1.6% annually between 2000 and 2015 [12] and last data shows that International shipping activities consume about 300 Mtonne of fuel per year [15]. In addition, global maritime trade grew by 2.4% in 2023 and it is expected to grow by 2%, with containerized trade potentially increasing by 3.5%, in forthcoming years [16]. With the increased number of ships visiting the ports, maritime emissions are expected to increase. Therefore, changes must be made urgently.

The IMO green initiatives, the IMO Initial Strategy on the reduction of GHG emissions from ships from 2018 and its upgrade from 2023, emphasize the need to reduce emissions in shipping, extending beyond open sea operations to include emissions from ships in ports [17].

Different emission control strategies can lead to reduction of emissions of greenhouse gases or emissions of local pollutants from shipping; however, current solutions cannot address all air pollutants simultaneously or at a reasonable cost [18]. Ports have more sources of emissions than only ships; ports host warehouses, buildings, cargo handling equipment or even industry [19] which makes decarbonization process even a greater challenge.

Nowadays ports place significant emphasis on both monitoring and improving their environmental performance [20]. For example, The Port Authority of Bari together with DBA Group developed a platform that that aims to link the environmental pollutants generated in the port area to port traffic, weather conditions and road viability [21]. In addition, in the past decades, a large number of actions and projects has been carried out to reduce the environmental footprint of port areas, especially in the European Union (EU) [22].

Decarbonization of seaports has become a critical step toward reducing global GHG emissions from shipping in general. Around 7% of CO2 emissions from the shipping are generated at berths in the ports of the European Economic Area [23]. As the EU has set the goal of reducing greenhouse gas emissions by at least 55% by 2030 and becoming climate-neutral by 2050, therefore European ports are facing sustainability and energy challenges, requiring changes to port functions, supply chain systems and business models [24].

Port decarbonization is the process through which a port achieves carbon neutrality and reduces other harmful emissions. This is accomplished by reducing CO2 emissions from all port activities to near-zero levels, while any surplus CO2 should be captured through carbon sinks or sequestrated [25]. Ports can change operational strategies or apply new technologies and energy management systems to address the problem of emissions [12]. Similar like in shipping, also in ports emission abatement technologies often necessitate trade-offs between cost, performance, and environmental impact [26].

3.1. Operational measures to decarbonize seaports

Operational measures are relatively quick and rather cheap to implement. Although they usually yield quick results, these improvements are not significant in terms of decarbonization of ports and are as such not enough to achieve carbon neutrality of the ports. These can be for example the implementation of differentiated dues in relation to the environmental performance of ships to attract cleaner ships ([27]; [28]), improvement of coordination and synchronization between ship and ports [29] and the definition of speed reduction zones for ships within the port aquatorium to directly reduce emissions ([30] ; [31]), trucks appointment system ([32]; [33]) as well as simplification [34] and automation of port entry/exit procedures ([35]; [36]) or longer gate opening hours and peak pricing strategies [37] to avoid congestion and trucks idling in and outside the port area, the installation of LED lighting to achieve energy savings [38] or eco-driving trainings to reduce fuel consumption. The most expensive amongst operational measures can be the promotion of low carbon hinterland transport as it usually necessitates also infrastructure investment [39].

It is difficult to monetise these measures, as they vary from case to case. Some of these measures do not imply any extra costs for ports, for example reduced speed in port aquatorium or better coordination between ships and ports; in fact, these measures can have positive impacts not only for air emissions in port area but also for shipping companies in form of reduced costs. Some measures can affect port's revenues instead of its costs; for example, the Port of Koper offers 5 to 10% discount on port fees for the arrival of cleaner ships based on Environmental Ship Index (ESI) with the maximum one-off discount being EUR 1,000 (interview) or promotion of modal shift in hinterland transport, but only if all necessary infrastructure is already built. On the other hand, truck appointment systems and other port-gate related measures imply certain investments and higher operating costs (e.g. additional employees), but result in higher productivity and in less congestion (probably also in higher support from local community). Also LED lighting initially assumes investments but given the fact the energy consumption significantly drops the payback period is short. Increased safety is usually an added value of the implementation of LED lighting,

3.2. Technological measures to decarbonize seaports

It is estimated that the global fleet of 100,000-120,000 Container handling equipment (CHE) in ports around the world emit 10-15 million tons of CO2 per year; this is equivalent to the annual emissions of Slovenia [40] The electrification of port equipment and vehicles is therefore a common approach to achieving improved energy efficiency and reduction of energy consumption and emissions in relatively short time. Usually, it takes from two to four years to start the operation with new equipment after the investment decision has been made. Electrification offers zero-emission performance [26]; however, studies show that in average electric rubber-tired gantry crane (e-RTG) achieves 86.6% energy savings and a 67.8% reduction in CO2 emissions in comparison to diesel RTG [41]. Vujičić et al. [42] quantified several other positive impacts of electrification of cargo handling equipment on container terminals; besides lower global warming potential (4.1 times), acidification potential (6.3 times), eutrophication potential (8.6 times) and photochemical ozone creation (7.5

times) are also much lower in comparison to standard diesel powered RTG. The replacement of diesel-powered cranes, trucks, and other handling equipment with electric alternatives requires high investment, but savings on fuel and maintenance occur during their lifespan [4]. Cost per unit for electric cable reel RTG cranes are marginally higher when compared to diesel units (as declared by Yuntai [43] currently in average around $2 million; however, prices are expected to be equalized after market demand allows electric equipment to be produced on a large scale [44]. Wei and Giuliano[45] estimated capital costs of $6.9 billion in 2019 value needed for the electrification of port equipment and vehicles in Los Angeles and Long Beach ports in the period from 2020 to 2045 and predicted a macroeconomic loss between $5.3 and 10 billion in gross state product due to relatively high electricity prices and high capital costs.

On-shore power supply (OPS) or cold ironing (CI) is an electrification alternative in the maritime sector used to reduce shipborne emissions by switching from diesel powered auxiliary generators to electricity when a ship berths at a port [46]. In 2020 there were 36 OPS installations in 31 EU ports [47], with the port of Zeebrugge being the first one to install it back in 2000. This technology is currently considered underutilized due to the high investment cost associated with shoreside installation and ship retrofitting [48]. Although Abu Bakar et al. [48] claim there are unclear benefits for ships and ports, studies show that the OPS reduces port emissions of CO2 by 48 to 70%, SO2 by 3 to 60%, NOx by 40 to 60%, black carbon emissions by 57 to 70% [49] providing wider environmental and human health benefits. OPS installation is therefore expected to be unavoidable in the long term for all port operators due to stringent emission policies; by the Regulation (EU) 2023/1804 ports of core TEN-T network will need to provide OPS to container and passenger ships.

OPS usage reduces CO2 emissions and emissions of local pollutants compared to berthing without OPS. The capital investment required for the OPS installation is estimated at approximately EUR 7.4 million, assuming the port's existing power grid meets the necessary standards. Considering the substantial external cost savings, estimated at around EUR 1.3 million annually, the total OPS-related expenditure is expected to be fully amortized within roughly seven years [50].

If supported by renewable energy, OPS and electrification make even more sense. In any case, transition to renewable energy can reduce the port's carbon footprint and enhance its resilience and sustainability. In addition, renewable energy sources in combination with an energy storage system can ensure a high degree of energy self-consumption [51]. Currently the average cost is $1.3 million per megawatt (MW) of electricity-producing capacity by wind turbine, but the cost varies around the world [52]. The price of photovoltaics is similar but can increase due to various factors. For example, in the port of Koper the installation of solar power plant is ongoing, and it should produce sufficient electricity to make the port energy self-sufficient, even when the OPS will be installed (interview).

In recent years, also the zero-carbon fuel, such as hydrogen, is considered more often together with the electrification process [53]. In fact, the REpowerEU plan launched in May 2022 prioritizes combining electrification with low-carbon hydrogen for a green energy shift in EU [54]. In February 2024 Kobe-Osaka international port corporation started cargo handling operations using a hydrogen-fueled RTG crane as the first port ever [55]. In the port of Valencia, they are testing several different hydrogen powered cargo handling machines. Currently green hydrogen prices range from $5 to over $12 per kilogram, depending on the production method used and delivery cost; however, the target price of 1$ per kilogram is set for 2031 [56]. Hydrogen produced from fossil fuels is cheaper, but as such has a very high carbon footprint.

Kavakeb et al. [57] stated that intelligent automated vehicles contribute to vehicle routing optimization and in this way enhance energy efficiency of the ports. In the future, the digital twin (DT) is likely to make a significant contribution to reducing emissions in and around the port as they enhance efficiency and streamline logistical processes [58]. DT is a modern concept; an upgrade of the digital model and digital shadow, providing bidirectional dynamic link between the physical object or system and its digital representation. It is meant to improve threat detection, achieve energy savings and cost reductions, provide increased performance, and finally enhanced collaboration [59] by real-time monitoring and management of cargo, equipment, and environmental conditions [60]. However, due to port's complexity, the creation of digital twin is time consuming and expensive; but once operating it can achieve up to 30% cost savings on logistics operations [61].

4. DISCUSSION AND CONCLUSIONS

The decarbonization of seaports is a multifaceted challenge that requires a combination of operational, technological, and strategic measures. This paper has highlighted that while operational measures, such as differentiated port dues, truck appointment systems, or eco-driving initiatives, are relatively low-cost and quick to implement, their impact on overall emissions is limited. These measures serve as important first steps but are insufficient on their own to achieve carbon neutrality. Technological interventions, particularly the electrification of port equipment and the implementation of OPS, offer more substantial emission reductions. However, they bear significant capital costs and infrastructural demands. The analysis shows that despite high upfront investments, technologies like OPS and electrification of terminal equipment can yield long-term savings and environmental benefits, especially when powered by renewable energy sources. The integration of renewable energy and energy storage systems further enhances the sustainability and resilience of port operations.

Emerging solutions such as hydrogen-powered equipment and digital twins represent the next steps in port decarbonization. Although promising, these technologies are still in the early stages of deployment and require further development.

From an economic perspective, the transition to low-carbon port operations involves trade-offs between environmental performance, financial feasibility, and operational efficiency. Achieving substantial decarbonization in seaports is possible but demands a tailor-made strategic mix of short-term operational improvements and long-term technological investments.

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OPTIMISM – ONLINE PROGRAMME FOR TRAINING ON INTERNATIONAL MANAGEMENT OF ISM CODE

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Abstract

The International Maritime Organization (IMO)'s Guidelines on Management for the Safe Operation of Ships and for Pollution Prevention, known as the International Safety Management (ISM) Code, became mandatory in 1998. The development of the ISM Code was prompted by several high-profile maritime accidents in the 1980s, most notably the capsizing of the Herald of Free Enterprise, a roll-on/roll-off passenger ferry, at Zeebrugge in March 1987. This tragic incident resulted in the loss of 193 lives out of the 539 passengers and crew on board and highlighted serious shortcomings in safety management and operational oversight.Twenty-five years later – after five amendments and several key provisions introduced under SOLAS Chapter IX relating to the ISM Code – the OPTIMISM project (Online Programme for Training on International Management of the ISM Code) was launched. This initiative is led by five European organisations with support from the European Commission. The primary aim of the OPTIMISM project is to evaluate the effectiveness of the ISM Code and its associated measures in improving safety and operational

standards across the shipping industry, and to recommend enhancements where needed. Running from September 2023 to August 2026, the project will deliver two major outcomes: (1) a comprehensive report on the current state of ISM Code implementation in the maritime sector, along with evidence-based recommendations for improvements; and (2) a fully developed, competence-based online training programme. This course will focus on the principles and practical application of the ISM Code and will include a novel assessment system featuring self-evaluation tools, written assignments, and an oral examination component.

Keywords: ISM Code, Maritime Safety, Marine Environment, learning from Accidents, Audits and Inspections

1. INTRODUCTION

International Safety Management Code (ISM) should be familiar to all mariners around the world. The ISM Code consist of 12 core elements and provides guidance on verification and certification processes, The purpose of ISM Code is to ensure the safety at sea, to prevent human injury or loss of life, to ensure marine environment protection and damage to the ship. To comply with the ISM Code, each ship must have a working Safety Management System (SMS) consisting following element: Commitment from top management, a top tier policy manual, a procedures manual, that vessel is following company SMS procedures for conducting both internal and external audits to ensure the ship is doing what is documented in the procedures manual, Designated Person Ashore (DPA) to serve as the link between the ships and shore personnel, a system for identifying where actual practises do not meet those that are documented and for implementing associated corrective actions and regular management reviews . Almost all ISM Code manuals are required to take ISO 9000 Quality System and ISO 14000 Environmental Management System into account. The problem is that any form of procedural quality system such ISM does not necessarily improve safety for this reason a novel online course on ISM Code requirements and all relevant safety, environmental and quality standards is needed. Furthermore, many smaller shipping companies are unable to apply international quality or management systems such as ISO 9000 due to resource limitations [1].

OPTIMISM team started the project with literature review divided into three chapters, ISM Code and associated rules and regulations, latest reports on or in support of the ISM Code and learning from Audits, Inspections and Accidents/Incidents. Review of some 60 accidents from 200 accident report reviews since 2010 was carried out. The accidents included a range of ship types covering collisions, grounding, capsizing, falling from heights, fire/explosion, exposure to hazardous gases in enclosed spaces and so forth. These accidents are broken down into several columns giving information including the accident number (1), vessel's name (2), type of vessel (3), type of accident e.g., collision or fire (4), actual description (5), cause of the accident (6), casualty (7), actions taken/recommendations (8) and stating if the accident will recur (9). In almost all cases the ISM element/sub-element causing or contributing to the accident is identified (10).

2. MARINE SAFETY INVESTIGATION REPORTS

Marine safety investigation reports selected for analysis in OPTIMISM-project were chosen totally random but other than seeking answers to several questions when interviewing a sample of key stakeholders. Whilst working on the review of the selected accident reports it was found that many of the reports were less than satisfactory regarding lacking comprehensive evidence to lessen the probability that these accidents would not be repeated. Many of the reports included inadequate explanations for their conclusions or were inappropriate or lacked substance. There were several inconsistencies for instance the nature of the casualties was not apparent or missing; there was no indication or reference to key organizations involved. This suggests that the investigators were not fully aware of the requirements of Safety Management Certificate (SMC) or Document of Compliance (DOC) viz., it was not clear which administration was involved or any reference to the ownership, the crew or their timesheets. The explanation on the human element mainly mentioned inadequacy of the training, in most cases in vague terms. There were discrepancies in the safety issues identified. The quality (fitness) of recommendations and actions were generally poor for the purpose of preventing these accidents occurring again. Indeed, in about half of the cases reviewed there was inadequate information for ensuring the accident would not happen again. In majority of cases, key and other contributing factors were hardly mentioned.

It was found difficult to rely on Global Integrated Shipping Information System (GISIS) and depended instead on the actions and recommendations made in the accident reports which have been corroborated with the findings of others such as a report submitted to the IMO, entitled 'Lessons Learned and Safety Issues Identified from the Analysis of Marine Safety Investigation Reports'. To this end, considerable effort was expended on developing a new system for reviewing accident reports. This focuses as to whether the main root cause was a Quality Assurance related deficiency (Error) or a human (or system) deficiency (Mistake) by finding out, from the information available in the accident reports, whether human element failures/factors (Mistake) were the main contributing factor or the ship quality assurance system/SMS (Error). Having studied the reports several important factors were identified. It was apparent that communication, human vulnerability and decision making were the most frequent occurrences with several other factors also playing a major role such as inadequate knowledge of the crew members or risk assessment by the company. When reviewing the accidents, a decision was made to also identify if there was a management fault and if this was the case whether manning was also an issue.

3. ACCIDENT INVESTIGATION REPORT ANALYSIS

A methodology was developed to extract notable information from these reports such as description of the accident, actions suggested by the investigators, main root causes of the accident and any other contributing factors such as inadequate risk-assessment, inadequate knowledge, inappropriate decision-making, poor supervision and so forth. A column was also devoted to the likelihood of this accident happening again focusing on the main task of investigating accidents by the investigators.

Figures 1 and 2 give details of the annual number of accidents by year and the types of ships involved in these accidents.

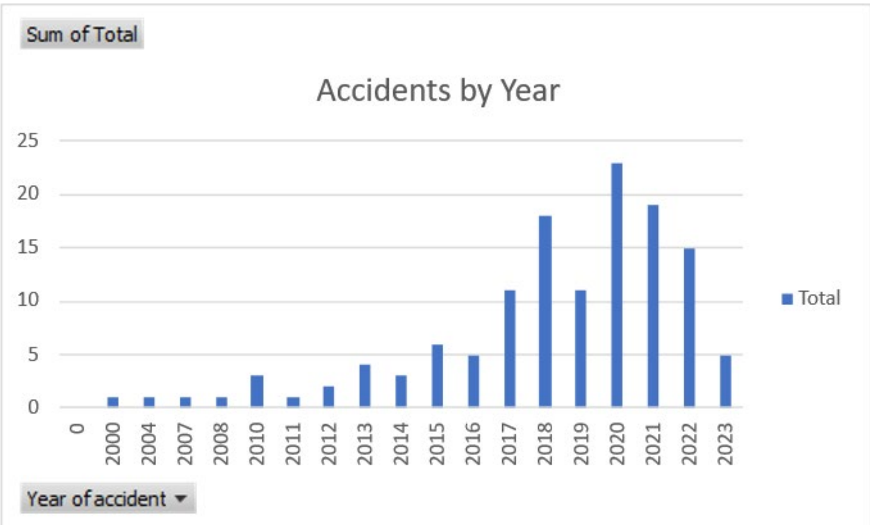

Figure 1 Accidents each year vs. Year of accidents (Source: Ziarati et al. 2025, Project OPTIMISM: Learning from Accidents, ISM Audits and Port Inspections TransNAV'25, Poland, 2025)

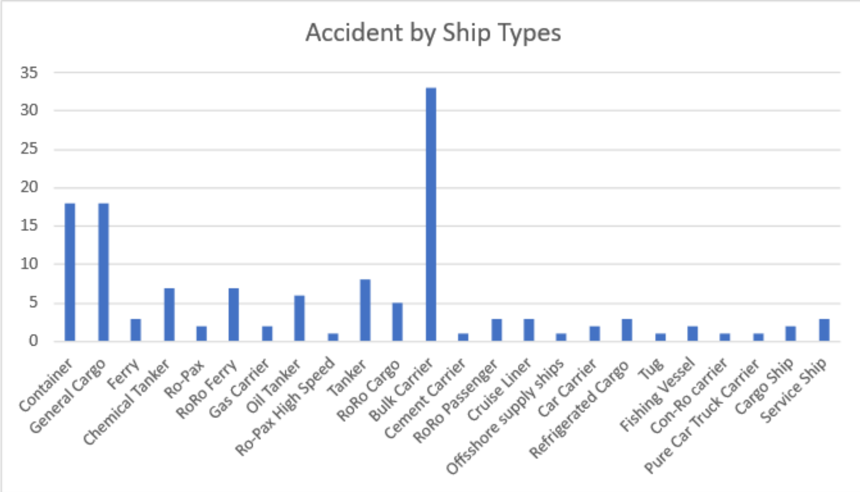

Figure 2 Number of accidents vs. Ship Type (Source: Ziarati et al. 2025, Project OPTIMISM: Learning from Accidents, ISM Audits and Port Inspections TransNAV'25, Poland, 2025)

In a study by Zachau [2] issues regarding analysis of accident investigation reports highlighted several areas of for improvements. The study was complemented by Ziarati et al. [3] and De Melo Rodriguez et al. [4]. The latter studies provided a new taxonomy of root causes of and contributing factors to accidents at sea and ports. The latter two studies examined the effectiveness of safety management systems and identified critical gaps in training effectiveness, risk perception, and the implementation of safety measures. The study found that many safety protocols were not adequately applied in real-world operational settings, with crew members struggling to retain and apply training under high-pressure conditions.

In this study information for preparing the table of accidents was obtained from Centre for The Future Factories' (C4FF) list of questions and causes of, and contributing factors to, accident to ascertain the main root causes of accidents while at the same time distinguishing between Mistakes, Errors, Recklessness, Lapse, Slip, Violation or Sabotage [3,4]. A sample of accident investigation review summaries are given below in Table 1:

Table 1 Example of the template developed for the micro-analysis of accident reports (OPTIMISM – Project)

GISIS Number	RZ/HK
Description	Grounding and capsizing due to unsafe passing distance to shore at high speed. The collision caused severe and fast income of water which led to the immediate loss of propulsion and general services.
Key Root Causes	*Crew-related (Mistake)* - Poor leadership and Team operation - Captain's inattention/distraction due to the presence of persons extraneous to Bridge watch and a phone call not related to the navigation operations. *Company-related (Error)/Management fault* - ISM non-conformity due to inadequate risk assessment - The General Emergency Alarm was not activated immediately after the impact. This fact led to a delay in the management of the subsequent phases of the emergency. The analysis of crew certification, of the Muster List (ML) and of the familiarization and training highlighted some inconsistencies in the assignment of duties to some Crew members.
Casualties	32 fatalities: 16 passengers, 4 crew and 4 still missing.
Action-Recommendation	It is worth summarizing that the human element is the root cause in the accident reported here, both for the first phase of it, viz., the unconventional action which caused the contact with the rocks, and for the general emergency management. A complete review of safety culture particular for after the first sign of collision showed issues with the scope of the *Minimum Safe Manning* (MSM) and with the Muster List (ML) – noting that the SOLAS regulation V/14.1 requires that the ship shall be Marine Casualties Investigative Body – C/S Company document Page 7 - sufficiently and efficiently manned. This regulation refers, but not in a mandatory way, to the *Principles of Safe Manning* adopted by the Organization by Resolution A.890(21) as amended by resolution A.955(23).
Would it happen again?	No if the Master was not distracted/inattentive and did not sail too close to the coastline and pass at an unsafe distance at nighttime and at high speed (15.5 kts).

The final stage in summarizing the accident was for each sub-focus group deciding what was the main root cause of the accident and as to whether Human Vulnerability, Decision Making or Communication played a role in causing the accident or contributed to making it worse immediately after.

It is interesting to note that majority of safety issues are Quality Assurance (QA) related while non-QA plays a major role either as the main root cause of accidents or as a contributing factor to it. In almost all cases there were deficiencies due to Human Vulnerabilities, Decision Making and Communication. In almost half of the accidents, it was noted that knowledge/skills/competence to be an issue. This clearly indicates that quality assurance of shipping companies is a problem area needing attention.

4. ONLINE TRAINING PROGRAMME

Besides a comprehensive report on the current state of ISM Code implementation in the maritime sector, along with evidence-based recommendations for improvements a fully developed, competence-based online training programme will be developed. This course will focus on the principles and practical application of the ISM Code and will include a novel assessment system featuring self-evaluation tools, written assignments, and an oral examination component. Also, appendixes including guidance for senior managers, ship crew and personnel at shore This training programme will be available free of charge fall 2026 at https://optimismproject.eu. (Figure 3)

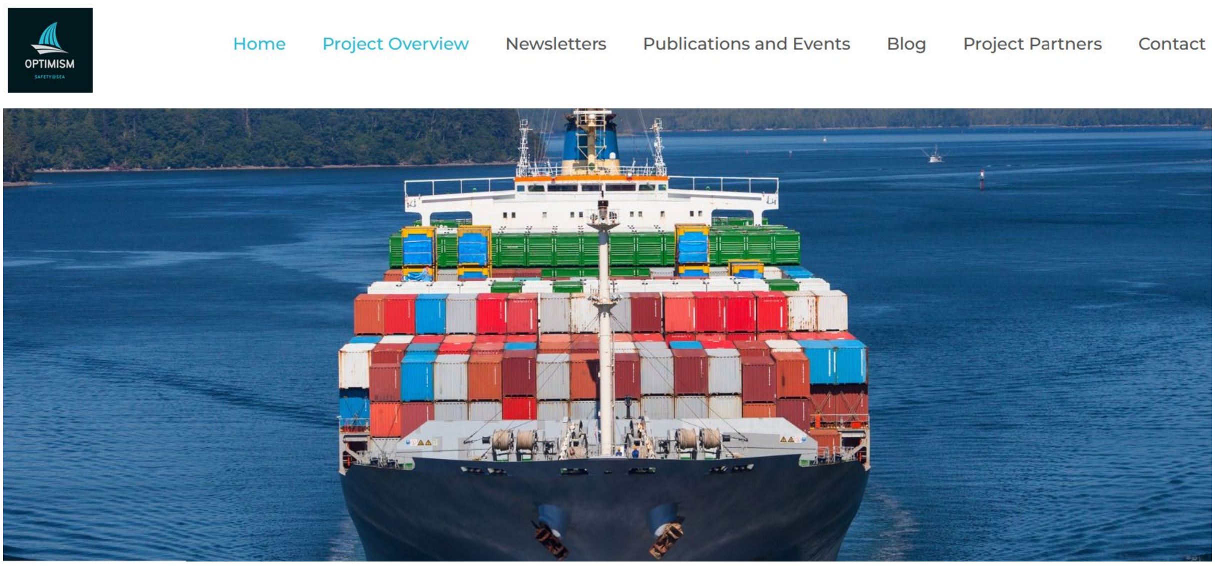

Figure 3 Screen shot of OPTIMISM home page, https://optimismproject.eu

All material and the link to the online programme can be found at OPTIMISM home page. Moodle platform will be used like in similar training projects earlier (Figure 4).

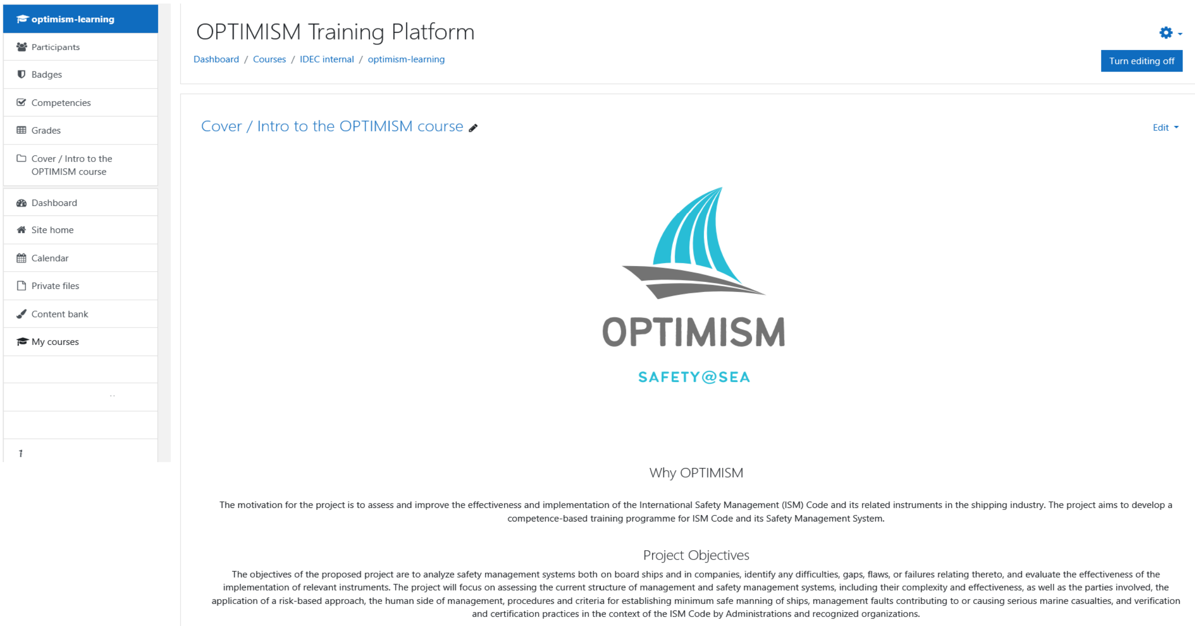

Figure 4 OPTIMISM moodle home page

5. CONCLUSION

In many cases the ISM deficiency should have been detected during an audit or an inspection. The problem is that even when non-conformities or deficiencies by International Association of Classification Societies (IACS) or Port State Control Officers (PSCOs) respectively are identified, a significant number of companies fail to take actions. It is particularly important to note that, in a survey conducted by C4FF [2,3] more than half of administrations and Recognised Organisations (Ros) had found evidence of repetitive deficiencies from previous ISM Code audits. This shows that there are a significant number of companies which do not take identified safety issues seriously.

Review of accident investigation reports was carried out with the aim of finding common safety issues and how they can be analysed effectively. The result was, inter alia, that a common safety issue was the lack of risk assessment, and that minority of the cases indicated ISM Code was not effectively implemented. As demonstrated in the sample case study (Table 1) here are several fuzzy areas where it is difficult to establish if there is a knowledge deficiency on the part of the crew member or that the company had not provided sufficient guidance or training on safety related matters.

Furthermore, three common main contributing factors to accidents were found to be ineffective communications, inappropriate decision-making and ignorance of human vulnerabilities.

The main output of this project is a complete competence-based online training programme on ISM Code and its implementation. There will be a novel assessment system covering self-assessment, assignments and an oral test. The programme will be Credit System for Vocational Education and Training (ECVET) and European Credit Transfer and Accumulation System (ECTS) compliant and will be submitted for accreditation and certification to a professional and internationally known professional body.

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