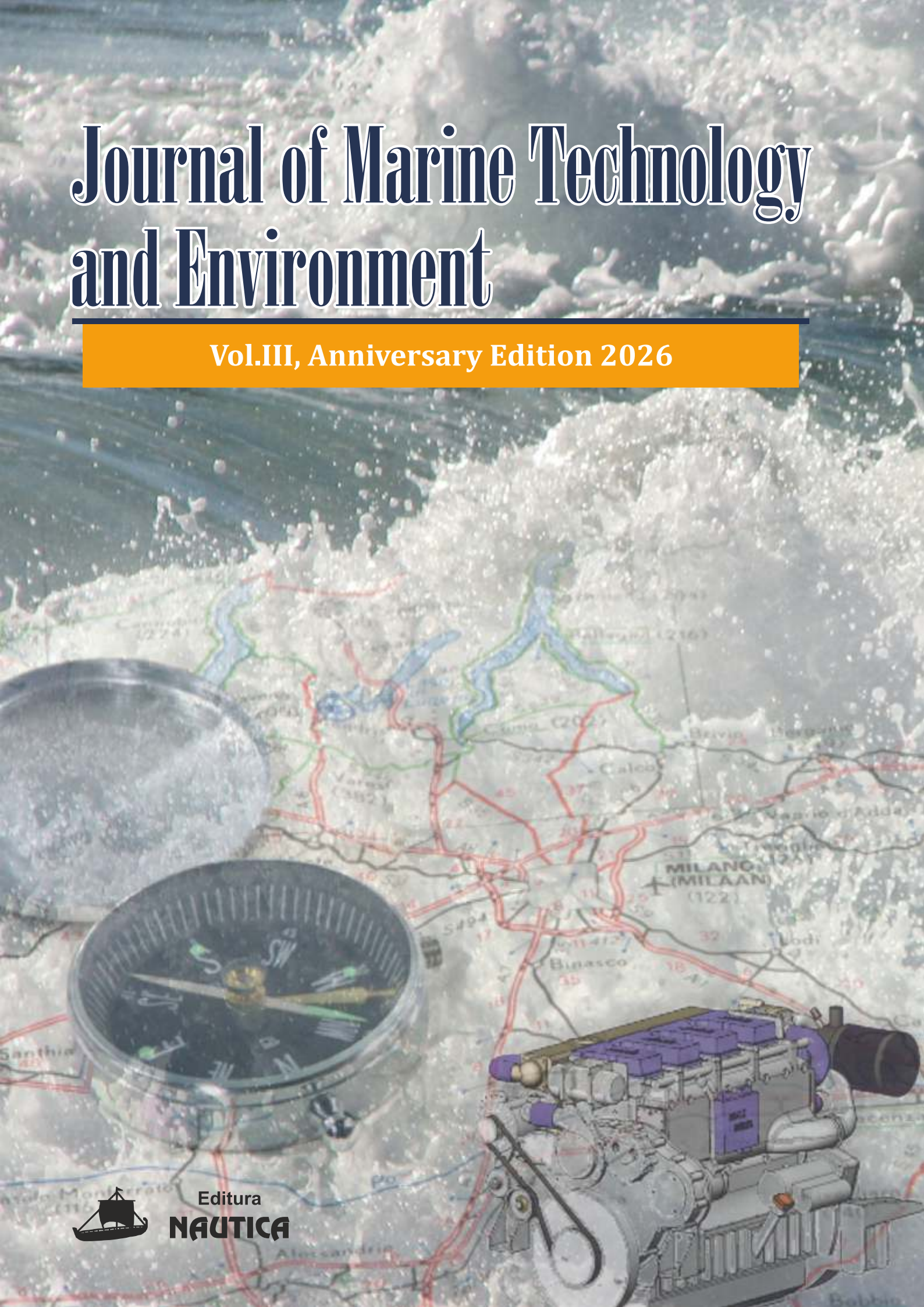
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GREENING MARITIME EDUCATION AT CONSTANTA MARITIME UNIVERSITY: INTEGRATING SUSTAINABILITY INTO TEACHING THROUGH RESEARCH AND COOPERATION

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Abstract: Constanta Maritime University (CMU) has educated officers and specialists for the maritime industry for many years, since the establishment of the Civil Marine Institute. This anniversary paper reflects on how the university adapts its teaching to the sustainability transition of shipping and ports, driven by the 2023 IMO Strategy on the reduction of greenhouse gas emissions from ships, the carbon intensity requirements of MARPOL Annex VI and the extension of the EU Emissions Trading System and of the FuelEU Maritime Regulation to maritime transport. The participation of CMU in the Erasmus+ project GREENPORT Alliances is presented as a case study that connects research, education and the port community. Several academic papers of the CMU team on port emissions, electric tugs, onshore power supply, on-board power management and the behaviour of educators and crews provided the evidence base for sustainability topics that can be integrated into existing courses and for a vocational course on sustainable maritime operations. The training course, centred on an eco-navigation simulator exercise, was piloted at CMU in four sessions between November 2025 and May 2026 with 20 deck officers, maritime pilots, tug masters, chief engineers and towage managers, evaluated with the Kirkpatrick model and the EQAVET quality cycle, and integrated into the CMU Training Centre portfolio. The experience is discussed through the COM-B model of behaviour change: research and trainer training build capability; the simulator, the institutional integration of the course and the journals and conferences create opportunity; and the comparison of the learners' own manoeuvres sustains motivation. The paper concludes that a lasting change of operational behaviour requires these three components to be developed together and outlines directions for the further greening of maritime education at CMU.
Key words: behaviour change, eco-navigation, maritime education and training, port emissions, simulator training, sustainability.

1. INTRODUCTION

Anniversaries of academic institutions and of their journals are an opportunity to look both back and ahead [15]. For Constanta Maritime University (CMU), whose origins go back to the Civil Marine Institute established in 1972 [1], the past five decades have been marked by a continuous adaptation of maritime education to technological change: from radar and satellite positioning to integrated bridge systems, electronic chart display and information systems (ECDIS) and, more recently, digital and cyber-physical ships and ports.

The current decade adds a new and pressing driver: the decarbonisation of shipping and port operations. The international and European regulations adopted since 2021 [2]-[6] have moved energy efficiency and greenhouse gas (GHG) emissions from the domain of ship design and policy into the daily decisions of seafarers and port professionals, as also illustrated by recent studies published in this journal [16], [17].

For maritime education and training (MET) institutions, sustainability can therefore no longer be treated as a separate or optional topic; it has to be embedded in the competences that graduates and practitioners use on the bridge, in the engine room and in the port.

The purpose of this paper is to describe how CMU responds to this challenge, with emphasis on the integration of sustainability topics into teaching, on applied research and on international cooperation. The GREENPORT Alliances Erasmus+ project [8], [9], in which CMU is a partner, is presented as a case study that connects applied research, course design, piloting with port professionals and dissemination, with a focus on an eco-navigation simulator session developed for pilots, tug masters, deck officers and port operations professionals [13].

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The following sections recall the main milestones of the university (Section 2), outline the regulatory and operational drivers (Section 3), describe the GREENPORT experience, from its research basis and teaching topics to the pilot at CMU (Section 4), and discuss the lessons learned through the COM-B model of behaviour change (Section 5); Section 6 concludes.

2. FIVE DECADES OF MARITIME EDUCATION IN CONSTANTA

Civilian maritime higher education in Constanta began with the establishment of the Civil Marine Institute in February 1972 [1]. In 1973 the institute was merged with the military officers' school, forming the "Mircea cel Batran" Marine Institute under the Ministry of National Defence. In 1990, by Government Decision no. 113 of 6 February 1990, the Civil Marine Institute was re-established under the Ministry of Education, with the faculties of Navigation and Electromechanics. In 2000 the institute became Constanta Maritime University, by Government Decision no. 85/2000 [1]. The date of 6 February is celebrated as the day of the university.

Over this period, the educational offer has grown from the two traditional pillars, navigation and marine engineering, to programmes in electrical engineering, transport economics and management and, more recently, cyber security. Today the university offers 11 bachelor and more than 15 master programmes to approximately 3,700 students. Programmes for seafarers have been continuously aligned with the STCW Convention [7], while the university has kept close links with the Port of Constanta, the largest port on the Black Sea, and with shipping companies, pilotage and towage operators. This proximity to the port community is an important asset for the sustainability transition discussed below.

3. SUSTAINABILITY DRIVERS FOR MARITIME CURRICULA

3.1 International and European regulatory framework

In July 2023 the International Maritime Organization (IMO) adopted its revised Strategy on the reduction of GHG emissions from ships. The Strategy sets the goal of reaching net-zero GHG emissions from international shipping by or around 2050, with indicative checkpoints of at least 20%, striving for 30%, reduction of total annual emissions by 2030 and of at least 70%, striving for 80%, by 2040, compared with 2008 [2]. Earlier amendments to MARPOL Annex VI introduced the Energy Efficiency Existing Ship Index (EEXI) and the operational Carbon Intensity Indicator (CII), in force since 1 November 2022, with annual ratings from A to E [3]. The CII is particularly relevant for education because it depends on how the ship is operated: speed, routing, trim, use of auxiliary engines and time spent in port.

At European level, maritime transport was included in the EU Emissions Trading System from 1 January 2024, with a progressive phase-in of the obligation to surrender allowances [4]. The FuelEU Maritime Regulation, applicable from 1 January 2025, limits the GHG intensity of the energy used on board and requires, from 2030, container and passenger ships at berth in the main EU ports to connect to on-shore power supply [5]. The Alternative Fuels Infrastructure Regulation obliges Member States to deploy shore-side electricity in these ports [6]. Together, these instruments give emissions a direct cost and a compliance dimension, which companies pass on to their crews and shore staff.

3.2 Ports and port services

Ports concentrate emissions close to urban areas, and an important share comes from activities that ship-based regulations do not cover, such as harbour towage, pilotage, mooring and cargo handling. GREENPORT Alliances starts from the observation that emissions from port services are largely unregulated and that technical solutions, such as new tug propulsion systems or alternative fuels, require time and investment [8]. In the meantime, the way in which pilots and tug masters plan and execute a manoeuvre directly determines how much power the ship and the tugs use. Operational behaviour is therefore an immediate and low-cost lever for reducing emissions, and it can be developed through training.

3.3 Implications for competences

These drivers translate into competences that need to be developed both in initial education and in lifelong learning:

- understanding of the regulatory framework and of the indicators used to assess energy and emissions performance;
- energy-efficient voyage, passage and manoeuvring planning;
- efficient use of propulsion, auxiliary systems and tug assistance;
- awareness of alternative fuels and of their safety implications;
- data literacy for monitoring, reporting and verification of emissions;
- teamwork and communication between the ship, the pilot, the tugs and the terminal.

The comprehensive review of the STCW Convention and Code under way at IMO is expected to reflect part of these needs. MET institutions, however, do not need to wait for it in order to update their teaching.

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4. THE GREENPORT ALLIANCES EXPERIENCE

GREENPORT Alliances (Erasmus+, project no. 101139879, February 2024 - January 2027) brings together ten partners from eight countries, coordinated by Piri Reis University, Türkiye. Besides Piri Reis University and CMU, the consortium includes AcrossLimits (Malta), the Antwerp Maritime Academy, the European Tugowners Association and the European Maritime Pilots' Association (Belgium), the "Nikola Vaptsarov" Naval Academy (Bulgaria), the Faculty of Maritime Studies of the University of Rijeka (Croatia), Mar.TE (Italy) and the Port of Aveiro (Portugal) [8], [9], so that higher education, the towage and pilotage professions and a port authority work together. The project aims to change the behaviour of current and future port services personnel by integrating sustainability, together with the EntreComp entrepreneurship competence framework [10], into new educational offers. Three training products are developed: a 4-ECTS academic course on eco-navigation and emissions tracking for maritime students, a vocational course for tug, pilot and port personnel, and a 20-hour train-the-trainer programme for maritime educators [9]. Within the consortium, CMU contributed to the research basis of the project, to the development and validation of the vocational course and to its piloting with port services personnel in Romania [26].

4.1 Research basis and teaching topics

The training products of GREENPORT were preceded and accompanied by applied research carried out by consortium partners. Between 2025 and 2026, the CMU team contributed to eight papers [18]-[25], which can be grouped in four strands (Table 1).

Table 1. Research strands of the CMU GREENPORT team and the sustainability topics they bring to teaching

Research strand	Main findings	Topics for teaching
Evidence reviews of port emission reduction [18]-[20]	Three themes for greener port services: • emission-reduction technologies, data-driven optimisation and governance (27 studies); • electric tugs cut emissions and noise but face high costs, limited range and charging needs (42 studies and an industry focus group); • onshore power supply is limited by grid capacity, compatibility and missing standards	• Green port technologies and port electrification; • Electric and hybrid tugs; • Alternative fuels and their safety; • Environmental management of port operations; • Case studies of green ports
Economics of shore power [21]	Under EU ETS carbon pricing, onshore power supply becomes economically viable, not only environmentally beneficial	• IMO and EU instruments (EU ETS, FuelEU Maritime, AFIR, MRV); • The cost of emissions in ship and port operation; • Shore power in commercial operation
On-board energy management, simulator-based [24], [25]	DP vessel generators work best at 75-90% load (thermal efficiency about 37%) with a spinning reserve of at least 15%; a power management system stabilises the grid of diesel-electric tugs at peak loads	• Energy-efficient manoeuvring and passage planning; • Route optimisation on ECDIS; • Generator loading and power management; • Reading power, fuel and emissions data
Human behaviour and educators [22], [23]	86 maritime educators are motivated to teach behavioural change but lack capability (training, resources) and opportunity (real cases, interactive methods); IoT monitoring of stress-related deck crew behaviour, validated with captains	• Bridge and watch team communication; • Human factors and stress; • Decisions under operational constraints; • Initiative and opportunity spotting (EntreComp); • Behavioural change approaches

Two of these results directly shaped the training. The COM-B survey showed that the main obstacles for educators are capability and opportunity rather than motivation [22], which supports the emphasis of GREENPORT on a train-the-trainer programme and on ready-to-use, simulator-based case material. The study of diesel generators on DP vessels [24] provided the method used to convert simulator power records into fuel consumption and emissions, by means of brake specific fuel consumption curves and emission factors, which was later applied in the CMU pilot (Section 4.5). The reviews also explain the operational focus of the course:

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technical solutions such as electric tugs or shore power require time, investment and infrastructure [19]-[21], whereas a change in manoeuvring practice can be trained immediately.

These topics fit into the existing structure of the bachelor programme in navigation, which already covers ship manoeuvring, voyage planning, electronic navigation and ECDIS, meteorology, pollution prevention and marine ecology, international and EU maritime regulation, port systems, watch team management and entrepreneurship in maritime transport. They can therefore be integrated into teaching as updated content, case studies and simulator exercises, without waiting for new study programmes, and the same material supports the vocational course for port services personnel.

4.2 The eco-navigation simulator session

Within the vocational course *Sustainable Maritime Operations and Green Port Technologies*, Session 7, Eco Navigation, is a four-hour instructor-led simulator exercise for pilots, tug masters, deck officers and port operations professionals [13]. A large commercial vessel approaches an enclosed dock basin with the wind from astern, swings to head into the wind and berths with the assistance of two harbour tugs. Trainees perform the same manoeuvre twice under identical initial and environmental conditions. In Run 1 they apply their usual professional practice; in Run 2 they apply an optimised plan, agreed jointly by the pilot and the tug masters during a structured debrief (Figure 1). Simulator-based exercises of this kind allow learners to observe the consequences of their own decisions in a safe environment and to repeat a task under identical conditions, which is rarely possible on board [11].

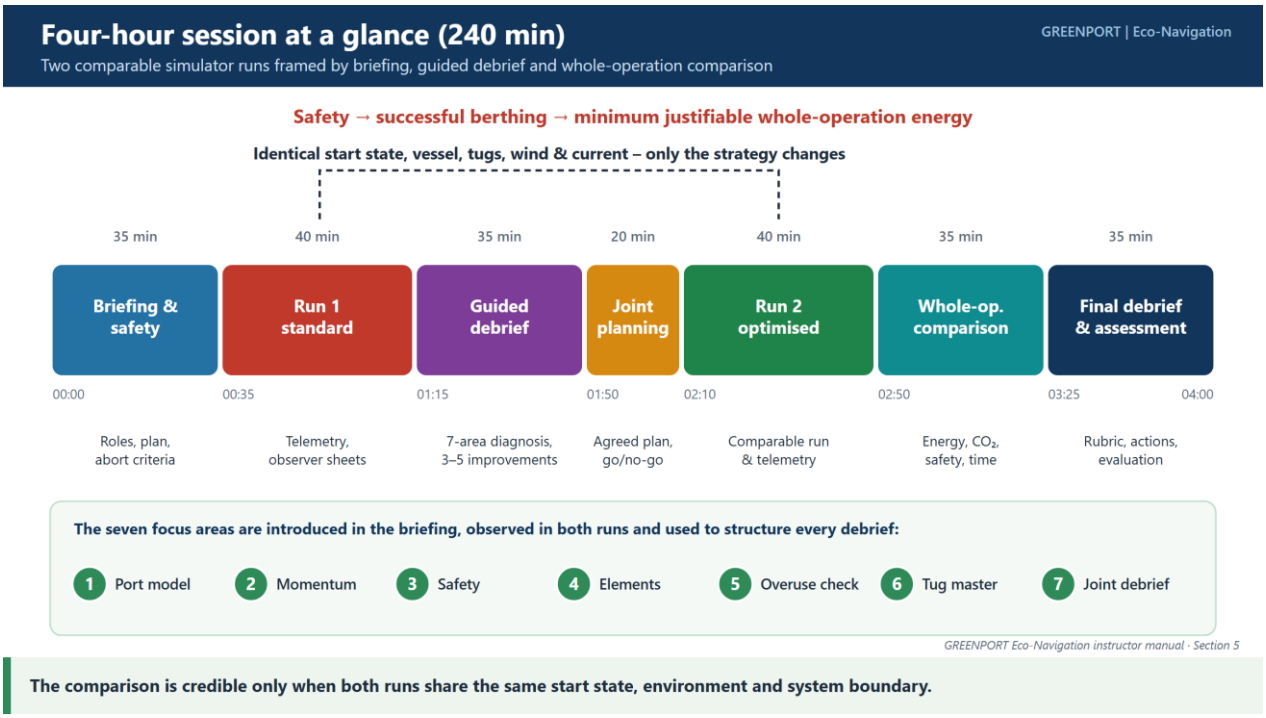


Figure 1 Structure of the four-hour eco-navigation session (illustrative) [13]

The session is designed to be replicable at different training centres and on different simulator platforms, such as Wärtsilä-Transas Navi-Trainer Pro 5000 or Kongsberg. At CMU, the session was implemented on the Kongsberg K-Sim Dynamic Positioning simulator (Section 4.5), which illustrates this transferability. A centre configuration sheet records the local port model, the vessel and tug models and the validated wind conditions. Where available, the instructor exports time-stamped engine and tug demand data; when tug engine-load data are not available, the requested bollard pull and its duration are used as an indicator [13].

The guiding principle is safety first, then a successful berthing, then the lowest justified energy use and emissions. Completion is based on participation and demonstrated reasoning, not on achieving a predetermined percentage of emission reduction, and a lower-energy run is not considered successful if safety limits are violated [13].

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4.3 Seven focus areas and the whole-operation comparison

The briefing introduces seven focus areas in which energy can be saved during the approach, swing and berthing (Figure 2): (1) port-specific digital modelling and planning of the swing; (2) strategic use of the vessel's momentum, by reducing main-engine power early and in stages; (3) prioritising safety in manoeuvring; (4) using wind and current to advantage instead of counteracting them; (5) monitoring for overuse of tugs and ship's engine, including propulsion demands that cancel each other out; (6) delivering tug assistance efficiently: the tug master's contribution; and (7) a joint post-operation debrief of pilots and tug masters [13].

A key element is that the two runs are compared for the whole operation, the assisted vessel and each tug, and not for the ship alone. Learners examine the manoeuvring time, the periods of high main-engine and tug load and the tug force-time demand, and ask whether total emissions fell or simply moved from the ship to the tugs [13]. This whole-operation view makes visible the shared responsibility of pilots and tug masters: every engine and tug order has an energy and emissions consequence.

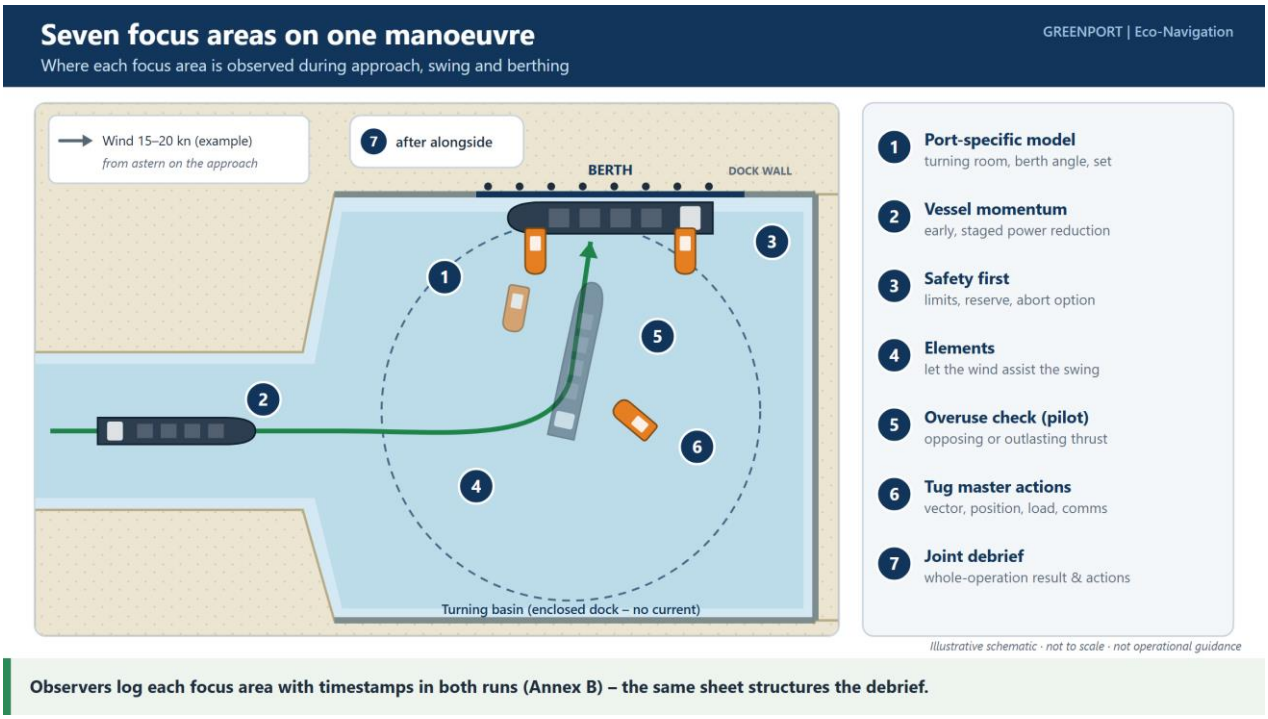


Figure 2 Seven focus areas for energy saving during a tug-assisted swing and berthing manoeuvre [13]

4.4 Evaluation framework

The effectiveness of the session is evaluated with the four-level model of Kirkpatrick [12], as summarised in Table 2. Learning is assessed through observation sheets, run data and a competence-based rubric, while behaviour and results are followed up after the course.

Table 2. Evaluation of the eco-navigation session with the Kirkpatrick model [12], [13]

Level	*Evidence collected*
1. Reaction	Participants' rating of the relevance and usefulness of the session
2. Learning	Competence-based assessment of decisions, coordination and whole-operation reasoning
3. Behaviour	Three practical actions committed by each participant for their own work, followed up after the course
4. Results	Operational evidence in port, such as fewer high-load periods and lower tug and engine demand

Levels 3 and 4 require cooperation with pilotage and towage operators beyond the classroom, which strengthens the links between the university and the port community. The model is complemented by the EQAVET quality assurance cycle of planning, implementation, evaluation and review [27], used to document how the evidence of each delivery informs the next one.

4.5 Pilot implementation at CMU

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CMU piloted the vocational course in four sessions between November 2025 and May 2026 with 20 participants: captains and deck officers, a chief engineer, experienced maritime pilots and the management and operational staff of a towage company, with a pilot from the Port of Aveiro, a project partner, as guest observer [26]. The sessions were conceived as successive validation stages, each refining the next: the first reviewed the methodology, the second tested the full sequence with initial and final knowledge assessments, the third refined the simulator exercise with experienced pilots and the fourth examined the applicability of the course to real tug operations. The course combines 8.5 contact hours, delivered online on the CMU Moodle platform or face-to-face and on the Kongsberg K-Sim Dynamic Positioning simulator, with about 6 hours of individual work, and was delivered by instructors trained in the GREENPORT train-the-trainer programme. The eco-navigation exercise confirmed that a planned manoeuvre, with steady thrust and use of wind and tide, needs less energy than a reactive one while remaining within safety limits; the scenario and the energy analysis are reported separately [24].

Evidence was collected at the first three Kirkpatrick levels: a post-course questionnaire on satisfaction, knowledge tests, which all formally assessed participants passed, complemented for experienced professionals by simulator observation and debriefing, and a follow-up questionnaire one month after the course on the application of learning. The debriefings converged on the same lessons: better planning reduces unnecessary power demand, small operational adjustments produce measurable reductions, communication between pilots and tug masters is essential for both safety and sustainability, and digital decision-support tools complement but do not replace professional judgement [26]. Level 4 evidence requires operational data from towage operators and remains to be collected.

4.6 Institutional integration and dissemination

Following the pilot, the course was formally integrated into the continuing professional development portfolio of the CMU Training Centre by decision of the University Senate, which secures its delivery beyond the lifetime of the project [26]. This step turns a project output into a permanent part of the educational offer of the university.

The results were also discussed with the wider maritime community. In September 2025, a stakeholders' roundtable gathered more than 25 representatives of port authorities, training centres, regulatory bodies, recruitment agencies and companies around the implementation of the EU MRV Regulation [26]. The international conference MariLog, organised by CMU, hosted in 2025 the round table Green Ports for Sustainable Maritime Future [28]. In 2026, the conference included a keynote address of the project coordinator on cooperation for sustainable development, a session on maritime transport trends with GREENPORT research, and an expert panel with DNV and the Romanian Naval Authority on the impact of ESG, CSRD, MRV, EU ETS and FuelEU Maritime requirements on workforce development and sustainability training [29].

5. DISCUSSION: A COM-B READING AND THE WAY FORWARD

The aim of GREENPORT is a change in the behaviour of port services personnel, not only an increase in knowledge. The COM-B model, which explains behaviour as the result of capability, opportunity and motivation [30], was used by the project team to study how maritime educators integrate sustainability into their teaching [22]. The same structure offers a useful reading of the CMU experience as a whole (Table 3).

Table 3. The CMU GREENPORT experience read through the COM-B model [22], [30]

COM-B component	How the CMU experience addresses it
Capability	Up-to-date content from the research of the CMU team (Table 1); knowledge of regulations and technologies; planning, timing and power-use skills practised on the simulator; instructors prepared through the train-the-trainer programme
Opportunity	Repeatable simulator scenarios and Moodle resources; course integrated into the CMU Training Centre portfolio; joint sessions of pilots, tug masters, engineers and managers; dialogue at MariLog and stakeholder events
Motivation	Learners see the effect of their own decisions in their own data; safety-first principle consistent with professional identity; structured debrief and personal commitments for their own work
Target behaviour	Planned and coordinated manoeuvres with fewer power peaks and less counteracting thrust, followed up at Kirkpatrick levels 3 and 4

Capability was built from two directions. The research of the CMU team supplied up-to-date content on technologies, regulations and energy management, and the train-the-trainer programme addressed the gap found among educators, who are motivated but report insufficient training and resources [22]. For learners, the comparison of two runs turns an abstract objective into concrete skills of planning, timing and power use, and the debrief, grounded in experiential learning [14], lets them build their own optimisation plan instead of receiving a prescribed solution.

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Opportunity is both physical and social. The simulator allows a manoeuvre to be repeated under identical conditions, and the integration of the course into the Training Centre portfolio keeps it available after the project. The joint participation of pilots, tug masters, engineers and managers, and the dialogue opened by MariLog and the stakeholder events, make energy use a shared concern of the port community rather than an individual one. Assessment opportunities must also fit the learners: written tests suit officers, while experienced professionals are better assessed through observation and professional discussion, and the two forms of evidence should be reported separately [26].

Motivation is strongest when learners see the effect of their own decisions in their own data. The finding that a slower, planned manoeuvre can be the greener one is more convincing when it emerges from a participant's run than when it is stated in a lecture. Placing safety explicitly before energy saving keeps the message consistent with the professional culture of pilots and tug masters and prevents savings at the expense of safe margins, while the personal commitments made at the end of the session connect reflection with practice. Read in this way, the experience suggests that the three components reinforce each other: knowledge without opportunity to practise, or practice without a convincing reason to change, is unlikely to change behaviour in port.

The approach has also started to travel beyond the consortium. GREENPORT Alliances has received a Letter of Intent from Race for the Baltic (RFTB), an initiative of the Baltic Sea region, to explore long-term cooperation in maritime research, innovation, sustainability and capacity building [31]. Within this cooperation, RFTB will pilot and evaluate the GREENPORT behavioural-change methodology in its own operational context, and the two initiatives will work towards a broader sustainability framework for ports, shipping and maritime communities. This transfer is also a test of the COM-B reading above: if capability, opportunity and motivation are developed together, a training approach designed for the Black Sea should be adaptable to the operational realities of another sea basin.

For CMU, the way forward includes integrating the GREENPORT outputs into bachelor and master curricula and into continuing professional development courses; extending simulator exercises to engine-room energy management and alternative fuels, and to hybrid and electric tugs [25]; developing data literacy for emissions monitoring and reporting; training the trainers, building on the capability gaps identified among educators [22]; measuring the capability, opportunity and motivation of course participants before and after training, with an instrument adapted from [22]; introducing a common observation rubric for simulator exercises across partner institutions; and cooperating with the Port of Constanta and port service providers to measure the effects of training in real operations. The approach also has limitations: simulator results depend on the fidelity of the ship and tug models, the pilot results rely on a small number of participants and runs, and the transfer of training to real operations has to be confirmed through follow-up at Kirkpatrick levels 3 and 4.

6. CONCLUSIONS

Over more than five decades, Constanta Maritime University has adapted its educational offer to successive technological changes in shipping. The sustainability transition requires a similar but faster adaptation, driven by the IMO GHG Strategy, the operational carbon intensity requirements and the European climate legislation for maritime transport.

This paper argued that integrating sustainability topics into teaching, supported by applied research, simulator-based learning and international cooperation, is an effective way to make every graduate and practitioner aware of their role in reducing emissions.

The GREENPORT Alliances project illustrates this approach: in a safe and repeatable setting, the eco-navigation session shows pilots and tug masters that their everyday manoeuvring decisions determine the energy use and emissions of the whole operation.

The pilot with 20 port professionals confirmed this in practice: the simulator exercise showed the lower energy demand of a planned manoeuvre, all formally assessed participants passed the final test, and the course has become a permanent part of the CMU Training Centre offer.

Read through the COM-B model, the experience shows that a lasting change of operational behaviour requires capability, opportunity and motivation to be developed together: research and trainer training build capability; the simulator, the institutional integration of the course and the dialogue with the port community create opportunity; and the experience of one's own data, within safety limits, sustains motivation.

Building on this experience, CMU can continue to contribute to a safer and greener maritime industry in the decades to come.

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9. DECLARATION

The authors declare the responsible use of Claude AI during the refinement of this manuscript. Assistance was limited to language polishing and structural alignment. All data analysis, interpretation, methodological decisions, and final writing were carried out under the full intellectual responsibility of the authors.

10. CREDIT AUTHORS STATEMENT

Conceptualization: N.A., T.A.; Investigation: N.A., T.A.; Methodology: N.A., T.A.; Project administration: T.A., N.A.; Visualization: N.A.; Writing - original draft: N.A.; Writing - review & editing: T.A., N.A.

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DESIGN AND REALIZATION OF A PROFILE NOTCHING DEVICE FOR AUTOMOTIVE ELASTOMER COMPONENTS

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Abstract: This paper presents the engineering design and constructive realization route of a profile notching device intended for automotive elastomer components manufactured in small and medium batches. Secondary profiling operations on rubber-based parts are difficult because elastomers combine low stiffness, large recoverable deformation, and sensitivity to local compression, which can generate dimensional scatter, tearing, or edge defects when conventional manual trimming is used. The proposed solution is a compact bench-mounted device built around a guided profiled punch, a dedicated locating nest, a stripper plate, an adjustable stop, and interchangeable cutting inserts. The study follows a structured design methodology including functional analysis, concept selection, preliminary force sizing, material selection, and risk-oriented constructive detailing. A representative load case is used to dimension the lever mechanism, punch holder, and frame under conservative assumptions. The resulting solution emphasizes repeatability, fast changeover, operator safety, and easy workshop manufacturing. The paper therefore offers a realistic mechanical-design basis for controlled notching of seals, gaskets, and similar elastomeric parts used in automotive assemblies.
Key words: Elastomer component; notching device; profile cutting; automotive manufacturing; tooling design; mechanical design.

1. INTRODUCTION

Automotive elastomer components such as sealing profiles, gaskets, cable grommets, and vibration-isolation elements are widely used because they combine flexibility, damping capacity, and resistance to aggressive service conditions. Their engineering behaviour is strongly influenced by large elastic strain, time-dependent deformation, and sensitivity to local stress concentration, which complicates secondary operations after moulding or extrusion [1-3].

In industrial practice, notching is often required to generate local assembly reliefs, corner joints, drainage features, or positioning references. When these cuts are made manually with knives or with simple open fixtures, productivity becomes operator-dependent and the final contour may suffer from local tearing, geometric deviation, or incomplete separation. The literature on elastomer cutting and machining shows that tool sharpness, fixture stiffness, and part support are decisive for process stability and cut quality [4-7].

The objective of this paper is to present the design and constructive realization route of a dedicated profile-notching device for automotive elastomer parts. The contribution is intentionally engineering-oriented: it translates material behaviour, tooling principles, and manufacturability constraints into a compact, workshop-feasible device architecture. Because the available case is primarily a design project, emphasis is placed on requirements definition, concept selection, preliminary sizing, and constructive detailing rather than on a full statistical production campaign.

2. DESIGN REQUIREMENTS AND ENGINEERING APPROACH

2.1 The sequential stages

The engineering approach included five sequential stages: identification of part and process requirements, generation of alternative concepts, weighted concept selection, preliminary sizing of the force path, and constructive detailing for manufacturing, adjustment, and maintenance. The target was not only to obtain a clean notch, but to do so with controlled positioning, reduced operator variability, and a structure that can be produced with standard workshop resources (Table 1).

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Table 1. Main design requirements for the proposed notching device

Requirement	Engineering target	Design implication
Cut quality	Clean profile without tearing	Sharp profiled punch and stable support
Dimensional repeatability	Constant notch position and depth	Dedicated nest and adjustable stop
Low part deformation	Limited local compression and slip	Contour support and stripper plate
Operator safety	Protected handling zone	Guarded actuation and controlled stroke
Quick changeover	Fast adaptation to new profiles	Interchangeable inserts
Maintainability	Simple sharpening and adjustment	Modular punch-die assembly

Three concept families were compared during the conceptual stage: an open knife guide, a screw-actuated vertical punch, and a lever-actuated guided punch with interchangeable inserts. The selection criteria were rigidity, repeatability, safety, changeover speed, manufacturability, and cost. The weighted assessment favoured the guided punch solution because it combines mechanical simplicity with a stable kinematic path and good operator feedback (Table 2).

Table 2. Weighted concept-selection matrix (authors' analysis)

Criteria	Weight	Open knife guide	Screw press	Lever guided punch
Rigidity of force path	25	2	4	5
Positioning repeatability	20	2	4	5
Operator safety	20	2	4	4
Change over speed	15	4	3	4
Manufacturing simplicity	10	5	3	4
Cost	10	5	2	4
Weighted total / 500	-	290	355	450

2.2 Functional design and preliminary sizing

The selected device is composed of a base plate, vertical side supports, an upper lever, a guided punch holder, a lower replaceable die insert, a contour-following nest, a stripper plate, an adjustable back stop, and a protected return spring. The elastomer part is positioned in the nest, constrained against lateral slip, and cut by a profiled blade moving on a controlled vertical path. The stripper plate limits elastic lifting of the workpiece and reduces the risk of the part sticking to the punch after separation.

Because elastomers deform significantly before fracture, the constructive philosophy was to minimize the unsupported span of the part, keep the tool path short and rigid, and maintain a small functional clearance between the profiled punch and the counter-support. Published studies on rubber cutting and elastomer milling show that work holding and tool geometry dominate process stability and surface quality, especially when the material is soft and highly compliant [6-7].

A representative design case was adopted to dimension the main components. The selected envelope corresponds to notches up to 30 mm effective length in parts up to 4 mm thickness. For preliminary sizing, the apparent cutting stress was conservatively taken as 4 MPa.

The estimated cutting force was therefore

$$F = \sigma \cdot A = 4 \times 10^{6} \times 30 \times 4 \times 10^{-6} \approx 480 \text{ N}. \quad (1)$$

To account for material variability, blade wear, and shock loading, the design force was raised to 1.2 kN. With a lever ratio of 1:6, the required nominal manual input becomes approximately 200 N, which remains acceptable for short-cycle manual operation. The frame, guide pins, and punch holder were therefore sized for a minimum static safety factor of 2 (Table 3).

Table 3. Preliminary sizing parameters for the representative design case

Parameter	Value/UM	Engineering role
Maximum part thickness	4 mm	Defines stroke and support geometry
Effective notch length	30 mm	Defines cutting area
Assumed apparent cutting stress	4 MPa	Conservative force estimate
Estimated cutting force	480 N	Initial load in the force path
Selected design force	1.2 kN	Robustness against

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		variability and wear
Lever ratio	1:6	Reduces operator effort
Nominal operator force	≈ 200 N	Ergonomic manual actuation
Minimum static safety factor	2	Structural reliability

From a constructive standpoint, the punch and die insert are specified from wear-resistant tool steel, while the structural frame may be produced from standard carbon-steel plates and machined spacers. Interchangeable inserts allow future adaptation to new notch geometries without rebuilding the complete device. Rubber-contact support areas should be smooth and, where necessary, backed by a compliant element to prevent local marking. Dimensional references for the finished parts must remain compatible with recognized rubber-product tolerance practice [8].

3. RESULTS AND DISCUSSION

3.1. Manufacturing and assembly

The realization route is intentionally compatible with a university workshop or a small industrial tool room. Base and side plates can be cut from steel plate and finish-machined on a milling machine. The guide set, punch holder, and adjustable stop can be produced by turning and drilling operations, while the insert contour is best manufactured by wire EDM or by finish grinding when high profile fidelity is required. Assembly begins with alignment of the base and guide elements, continues with installation of the lower insert and locating nest, and ends with adjustment of the punch stroke and the back stop.

3.2. Risk control and preventive measures

Preventive design measures were introduced early to reduce the most probable failure modes: blade wear, part slip, guide misalignment, incomplete cut, and accidental finger access. This type of risk-oriented detailing is essential because elastomer cutting is highly sensitive to local geometry and to the repeatability of the work holding condition (Table 4) [4-10].

Table 4. Preliminary sizing parameters for the representative design case

Potential issue	**Likely effect**	**Preventive measure**
Blade wear	Tearing and burr-like defects	Sharp enable insert and inspection intervals
Part slip in the nest	Wrong notch position	Back stop and contour support
Guide misalignment	Non-uniform cut and edge damage	Precision pins and adjustable setup
Insufficient stroke	Incomplete separation	Mechanical stop calibration
Operator contact with tool zone	Safety incident	Guarded actuation area and safe loading sequence

4. CONCLUSIONS

The paper presented an engineering route for the design and realization of a profile notching device dedicated to automotive elastomer components. The adopted solution, based on a guided profiled punch, a dedicated locating nest, and interchangeable inserts, was selected because it offers a favourable balance between repeatability, simplicity, safety, and manufacturability. Preliminary sizing based on a representative cutting case led to a design force of 1.2 kN and confirmed the feasibility of manual actuation through a lever mechanism.

From a practical perspective, the device can reduce dependence on manual knife trimming and can create a more controlled route for producing assembly notches in seals, gaskets, and similar parts. The modular tool concept also facilitates adaptation to different profiles without redesigning the entire structure. Future work should include prototype validation, direct force measurement, assessment of edge quality and dimensional repeatability, and optimization of punch geometry for different elastomer hardness classes.

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GREEN FINANCE AND THE EVOLVING ROLE OF INSURANCE IN MARITIME SUSTAINABILITY

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Abstract: The maritime industry is a vital component of global trade and economic development, yet it faces growing pressure to adopt sustainable practices in response to environmental challenges and climate change. This paper examines the growing role of green finance in supporting maritime sustainability initiatives, focusing on innovative financial instruments and investment strategies designed to mitigate environmental impacts. Additionally, it examines the evolving function of insurance in promoting sustainable practices, including coverage for eco-friendly vessels, emissions reduction technologies, and climate risk mitigation. The integration of green finance and specialized insurance solutions offers a comprehensive approach to fostering a resilient and environmentally responsible maritime sector. The paper concludes with policy recommendations and prospects for aligning financial mechanisms with sustainable maritime development goals.
Key words: Climate risk mitigation, eco-friendly vessels, green finance, emissions reduction technologies, investment strategy.

1. INTRODUCTION

1.1 Importance of sustainable development in the maritime sector

Maritime shipping accounts for approximately 2-3% of global greenhouse gas emissions (IMO, 2021). The maritime sector is a cornerstone of global trade, responsible for transporting approximately 80-90% of the world's goods by volume. It enables the movement of raw materials, manufactured products, energy resources, and agricultural commodities across continents, connecting economies and supporting international commerce. The sector's efficiency, cost-effectiveness, and ability to handle large volumes make it indispensable for the global supply chain. However, despite its crucial role, the maritime industry faces several significant challenges:

- *Environmental Impact*: Shipping contributes to greenhouse gas emissions, air and water pollution, and marine debris. Efforts to reduce its carbon footprint are ongoing but require substantial technological and regulatory advancements.
- *Regulatory and Security Concerns*: Stringent international regulations, such as the IMO sulfur emissions limits, and security threats, including piracy, particularly off the coast of Somalia and in other high-risk areas, pose operational challenges.
- *Technological Disruption*: The industry must adapt to new technologies, such as automation, digitalization, and greener fuels, which require substantial investment and infrastructure changes.
- *Economic Volatility*: Fluctuations in global markets, trade disputes, and economic downturns can impact shipping demand and profitability.
- Infrastructure Limitations: Ports, shipping lanes, and logistics hubs require continuous upgrades to handle larger ships and increased traffic efficiently.
- *Labor and Safety Issues*: Ensuring crew safety, managing labor shortages, and maintaining a skilled workforce are ongoing concerns.

While the maritime sector is vital for facilitating global trade, it must navigate environmental, technological, regulatory, and economic challenges to sustain its crucial role in the world economy.

1.2 Overview of green finance and insurance's role in the maritime industries

Innovative green finance and insurance solutions are crucial drivers in advancing sustainable development, providing the tools and mechanisms necessary to address environmental challenges while promoting economic growth. Their importance can be highlighted through several key points:

- *Mobilizing Capital for Sustainable Projects*: Green finance directs investments toward

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environmentally sustainable initiatives, including renewable energy, energy efficiency, clean transportation, and conservation projects. Innovative financial instruments, like green bonds and climate-focused funds, facilitate the flow of private and public capital into these vital areas.

- *Risk Mitigation and Resilience Building:* Green insurance solutions help manage climate-related risks, providing coverage for natural disasters, crop failures, and infrastructure damage caused by climate change. This encourages investment in resilient infrastructure and sustainable practices, reducing vulnerabilities and fostering long-term stability.
- *Encouraging Innovation and Market Development:* The development of innovative financial and insurance products stimulates the creation of new markets and technologies, fostering growth and development. For example, parametric insurance and weather derivatives enable farmers and businesses to hedge against climate variability, promoting sustainable economic activities.
- *Aligning Financial Incentives with Sustainability Goals:* Green finance and insurance integrate environmental, social, and governance (ESG) criteria into decision-making processes. This alignment incentivizes corporations and investors to adopt sustainable practices, contributing to global climate and environmental objectives.
- *Supporting Policy Goals and International Commitments***:** These solutions play a crucial role in achieving commitments under agreements such as the Paris Agreement and the Sustainable Development Goals (SDGs). They provide the financial backbone necessary for countries to meet their climate targets and promote inclusive, sustainable development.
- *Enhancing Public-Private Partnerships:* Innovative financial mechanisms foster collaboration between governments, the private sector, and civil society, creating a synergistic approach to sustainable development challenges.

Innovative green finance and insurance solutions are crucial for unlocking capital, managing risks, and incentivizing the actions necessary to build a more sustainable and resilient future. They not only support environmental preservation but also promote economic growth, social inclusion, and the achievement of global sustainability targets.

2. PURPOSE AND SCOPE OF THE PRESENTATION

2.1 Understand the Concept of Green Finance

Green Finance refers to financial investments that are directed towards projects, initiatives, and assets that promote environmental sustainability and address climate change. It aims to support the transition to a low-carbon, sustainable economy by mobilizing funds for activities that have positive environmental impacts.

Green finance refers to financial activities—such as investments, loans, and securities—that support environmentally sustainable projects and initiatives. It aims to promote economic growth while reducing environmental risks and ecological impacts. This includes funding renewable energy projects, energy efficiency improvements, pollution control measures, sustainable agricultural practices, and conservation efforts.

Green finance encompasses the allocation of financial resources—such as loans, bonds, insurance, and investments—towards projects and companies that contribute to environmental protection, resource efficiency, renewable energy, pollution reduction, and climate resilience.

Green finance is a broad and evolving field that aims to foster economic growth while ensuring environmental sustainability. Its scope encompasses various sectors, financial instruments, and initiatives focused on addressing environmental challenges.

- **Scope of Green Finance:**
  - *Renewable Energy Projects*: Funding solar, wind, hydro, geothermal, and other renewable energy sources
  - *Energy Efficiency:* Investing in energy-saving technologies in buildings, industries, and transportation.
  - *Pollution Control*: Supporting initiatives to reduce emissions, waste management, and water treatment.
  - *Sustainable Agriculture and Forestry*: Promoting practices that conserve biodiversity and reduce environmental impact.
  - *Climate Adaptation and Resilience*: Financing infrastructure and projects that help communities adapt to climate change impacts.
  - *Green Bonds and Securities*: Issuance of bonds designated explicitly for funding environmentally beneficial projects.
  - *Carbon Markets and Offsets*: Facilitating trading schemes to reduce greenhouse gas emissions.
  - *Sustainable Infrastructure*: Developing eco-friendly transportation, waste management, and urban planning solutions.

- **Key Stakeholders:**
  - Governments and policymakers
  - Financial institutions (banks, investment funds)

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- Corporations and industries
- Investors (institutional and retail)
- International organizations and development banks

- **Key Features of Green Finance:**
  - Focuses on environmentally beneficial outcomes
  - Supports renewable energy, clean technology, and sustainable infrastructure
  - Incorporates environmental risks into financial decision-making
  - Often involves green bonds, green loans, and ESG (Environmental, Social, and Governance) investing

- **Key Drivers of Green Finance:**
  - Climate change mitigation and adaptation
  - Regulatory policies and international commitments (e.g., Paris Agreement)
  - Investor and consumer demand for sustainable practices
  - Instruments of Green Finance
  - Green bonds and loans
  - Sustainability-linked loans
  - Grants and subsidies

- **Importance of Green Finance for Sustainable Development:**
  - *Mitigates Climate Change*: Facilitates investment in renewable energy sources, reducing reliance on fossil fuels and lowering greenhouse gas emissions
  - *Promotes Environmental Conservation*: Funds projects that preserve biodiversity, manage natural resources sustainably, and reduce pollution.
  - *Encourages Economic Resilience*: Builds a resilient economy by transitioning to sustainable industries that can withstand environmental shocks.
  - *Supports Social Equity*: Ensures that the benefits of sustainable development reach diverse communities, fostering inclusive growth.
  - *Aligns with Global Goals*: Contributes to achieving the United Nations Sustainable Development Goals (SDGs), particularly those related to clean energy, climate action, and sustainable cities.

Green finance also encompasses financial instruments and mechanisms designed to support sustainable and environmentally-friendly projects, initiatives, and investments. Here are some of the key financial instruments and mechanisms of green finance:

- **Key Financial Instruments of Green Finance**
  - *Green Bonds*

Bonds are specifically issued to fund environmentally sustainable projects, such as renewable energy, energy efficiency, and conservation initiatives. Examples include Climate Bonds, Sovereign Green Bonds, and Corporate Green Bonds.

  - *Green Loans*

Loans are provided for projects with environmental benefits, often with favorable terms or specific use restrictions. Green loan principles often emphasize transparency and measurable environmental outcomes.

  - *Green Equity Investments*

Equity funding in renewable energy companies, green startups, or sustainable infrastructure projects. Venture capital and private equity funds focusing on green innovations.

  - *Sustainable and Impact Investment Funds*

Investment funds that target companies and projects with positive environmental and social impacts. Incorporate Environmental, Social, and Governance (ESG) criteria.

  - *Blended Finance*

Use of concessional funds or grants to leverage additional private sector investment in green projects. Aimed at reducing risk and improving project bankability.

  - *Green Insurance Products*

Insurance policies that cover risks related to climate change or environmental damage. Examples include weather-related crop insurance or renewable energy project insurance.

- **Carbon Markets and Carbon Pricing Instruments**

Cap-and-trade systems and carbon offset mechanisms that put a price on carbon emissions. Facilitates funding for low-carbon projects via trading emissions allowances

2.2 Key Financial Mechanisms of Green Finance

  - *Public-Private Partnerships (PPPs)*

Collaborative arrangements between government and private sector entities to finance and operate green infrastructure projects.

  - *Government Grants and Subsidies*

Financial support from governments to promote green initiatives, reduce investment costs, or incentivize sustainable practices.

  - *Regulatory Frameworks and Standards*

Policies like tax incentives, renewable energy certificates, or mandatory disclosure regulations promote green investments.

  - *Guarantee Schemes*

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Financial guarantees provided by governments or institutions to reduce the risk for investors in green projects.

- *Climate Funds*

International funds such as the Green Climate Fund (GCF) provide financial support to developing countries for climate adaptation and mitigation.

- *Tax Incentives and Credits*

Tax benefits for investments in renewable energy, energy efficiency, or other green projects.

- *Sustainable Development Goals (SDGs) Alignment*

Integrating green finance mechanisms with SDGs to attract investments aligned with global sustainability targets (Table 1).

Table 1. Key Financial Mechanisms of Green Finance

Instrument/ Mechanism	Purpose	Examples
Green Bonds	Raise capital for green projects	Climate Bonds, Sovereign Green Bonds
Green Loans	Fund environmentally beneficial projects	Green Loan Principles
Green Equity	Invest in green companies	Green Venture Capital
Impact Funds	Promote ESG investing	Sustainable Investment Funds
Blended Finance	Leverage private investment	Concessional funds + private capital
Climate Markets	Price carbon emissions	Cap-and-trade, offsets |
Public-Private Partnerships	Shared investment risk	Infrastructure projects
Government Incentives	Encourage green investments	Tax credits, subsidies

2.3 Explore the role of policy frameworks and international standards promoting green finance

Policy frameworks and international standards play a crucial role in promoting green finance by creating a conducive environment, establishing credibility, reducing risks, and aligning investments with global sustainability goals. Here is an in-depth exploration of their roles:

- **Role of Policy Frameworks in Promoting Green Finance**

1. Creating a Supportive Regulatory Environment

Governments establish laws, regulations, and policies that incentivize green investments, such as renewable energy targets, emission reduction commitments, and green procurement policies.

Examples: Renewable Portfolio Standards, emission trading systems, and subsidies for clean energy.

2. Providing Financial Incentives

Tax incentives, grants, subsidies, and preferential loan terms encourage private sector participation in green projects.

These incentives lower investment costs and enhance project bankability.

3. Developing Green Finance Strategies and Roadmaps

Countries develop national strategies outlining how to integrate green finance into broader economic and environmental policies.

These strategies foster coordinated efforts and mobilize resources.

4. Establishing Green Certification and Labelling

Frameworks for certifying green projects or financial products (e.g., green bonds) increase transparency and investor confidence.

Examples: Green Bond Principles, Climate Bonds Standard.

5. Enhancing Disclosure and Transparency

Policies mandating ESG disclosures, climate risk reporting, and sustainability reporting improve investor information and decision-making.

Examples include the SEC Climate Disclosure Rules and the EU Sustainable Finance Disclosure Regulation (SFDR).

6. Risk Mitigation and Guarantee Schemes

Governments may establish guarantee funds or insurance schemes to reduce perceived risks and attract private investment into green projects.

- **Role of International Standards in Promoting Green Finance**

1. Providing Common Frameworks and Definitions

International standards establish universally accepted definitions of "green" and "sustainable" projects and investments, reducing ambiguity.

Examples: Green Bond Principles (GBP), Climate Bonds Standard.

2. Enhancing Credibility and Investor Confidence

Standards serve as benchmarks for due diligence, ensuring that green finance products meet specific

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environmental and social criteria. This reduces greenwashing and increases investor trust.

3. Facilitating Cross-Border Investment and Market Development
Harmonized standards enable investors to compare green assets across countries, fostering international investment flows. They also support the development of global green finance markets.

4. Supporting Risk Assessment and Management
Standards like those from the Task Force on Climate-related Financial Disclosures (TCFD) help investors assess climate-related risks. This encourages better risk management and integration of climate considerations into financial decision-making.

5. Aligning with Global Climate Goals
International agreements such as the Paris Agreement influence standards and frameworks to ensure that green finance aligns with global climate mitigation and adaptation targets.

6. Promoting Capacity Building and Knowledge Sharing
International organizations (e.g., UNEP FI, World Bank, IFC) provide guidance, best practices, and technical assistance to countries developing green finance policies.

- **Interplay Between Policy Frameworks and International Standards**
  - *Complementarity*: National policies often adopt or adapt international standards to ensure global consistency and credibility.
  - *Leverage*: International standards can help countries develop their policies more effectively by providing proven frameworks and best practices.
  - *Alignment*: Both aim to align financial flows with sustainable development and climate goals, creating a unified global approach (Table 2).

Table 2. Policy Frameworks and International Standards

Aspect	Role	Examples
Policy Frameworks	Create an enabling environment, incentives, transparency, and risk mitigation.	Renewable energy policies, green bond regulations, and disclosure laws
International Standards	Provide credibility, harmonization, risk assessment tools, and global benchmarks.	Green Bond Principles, TCFD, Climate Bonds Standard, SDGs

Effective policy frameworks and international standards are essential for scaling up green finance. They foster investor confidence, ensure transparency, reduce risks, and align financial flows with global sustainability and climate objectives. Together, they facilitate the transition toward a more sustainable and resilient economy.

3. ANALYSE THE ROLE OF GREEN FINANCE IN THE MARITIME SECTOR

Green finance plays a crucial role in supporting sustainable projects by directing financial resources toward initiatives that promote environmental protection, social well-being, and economic resilience. Here is an analysis of how green finance facilitates such projects:

1. Mobilization of Capital for Sustainable Development
Green finance channels both public and private funds into projects that generate positive environmental impacts. This includes investments in renewable energy, energy efficiency, clean transportation, sustainable agriculture, and conservation efforts. By providing targeted funding, green finance accelerates the transition to a low-carbon and sustainable economy
2. Risk Mitigation and Incentives
Green financial instruments, such as green bonds, green loans, and sustainability-linked loans, often come with favourable terms, including lower interest rates or longer tenures. These incentives encourage investors and lenders to finance environmentally sustainable projects, which might otherwise face higher perceived risks or uncertainty.
3. Promotion of Innovative Technologies
Green finance supports the development and deployment of innovative technologies, including solar, wind, bioenergy, and smart grid solutions. By providing the necessary capital, green finance helps overcome initial high costs and market barriers associated with new sustainable technologies.
4. Enhancing Transparency and Standards
Green finance often involves adherence to environmental, social, and governance (ESG) criteria and standards. This promotes transparency and accountability, ensuring that funds are genuinely directed toward sustainable projects. Instruments like green bonds typically require rigorous reporting and impact assessment, fostering trust among investors.
5. Policy and Regulatory Support
Governments and international organizations promote green finance through supportive policies, regulations, and frameworks. These include tax

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incentives, subsidies, or mandatory disclosure requirements, which further encourage investments in sustainable projects.

6. Addressing Climate Change and Environmental Challenges

Green finance directly contributes to reducing greenhouse gas emissions by funding renewable energy and energy efficiency projects. It also supports adaptation efforts, such as flood defences and resilient infrastructure, helping communities better manage climate risks.

7. Fostering Economic Growth and Job Creation

Sustainable projects financed through green finance often lead to new industries and employment opportunities in renewable energy, green construction, and environmental management sectors, contributing to sustainable economic growth.

Green finance supports sustainable projects by providing targeted capital, fostering innovation, ensuring transparency, and aligning financial flows with environmental and social objectives. It catalyses the transformation of economies towards sustainability, addressing pressing global challenges such as climate change, resource depletion, and social inequality.

3.1 Investigate case studies of successful green finance applications in maritime projects

Several notable case studies demonstrate the successful application of green finance in maritime projects. These examples highlight how innovative financing mechanisms have facilitated sustainable development within the maritime sector (Table 3).

- **Key Success Factors:**
  - ➢ Use of green bonds and blended finance to mobilize private capital like The Green Bond for the Port of Rotterdam (Netherlands)
  - ➢ Public-private partnerships to share risks and benefits like The Green Maritime Methanol Project (Singapore)
  - ➢ Focused investments on technological innovation and infrastructure like The European Investment Bank (EIB) Financing for Sustainable Maritime Infrastructure l
  - ➢ Strong regulatory and policy support aligning financial incentives with sustainability goals like The Green Shipping Program – The Maritime Green Investment Fund (Norway).

4. EXPLORE THE EVOLVING ROLE OF INSURANCE IN MARITIME

Understand traditional maritime insurance and its limitations.

Let us break down traditional maritime insurance and then explore its limitations in the context of green finance.

4.1 Traditional Maritime Insurance

It provides coverage for ships, cargo, and liabilities related to maritime operations. It typically includes policies like hull insurance, cargo insurance, protection and indemnity (P&I) insurance, and war risk insurance.

Key Features:

- ✓ Coverage of physical assets: Ships, cargo, equipment.
- ✓ Liability coverage: Protects against claims from third parties, environmental damage, or accidents.
- ✓ Risk assessment: Based on historical data, vessel age, route, cargo type, etc.
- ✓ Premiums: Calculated according to the perceived risk of incidents, damages, or losses.

- **Limitations of Traditional Maritime Insurance in Green Finance**

Green finance aims to promote sustainable investments and environmentally friendly practices. When integrating this with maritime activities, traditional insurance faces several limitations:

1. *Limited Incentives for Sustainable Practices:*

Traditional policies do not typically incentivize eco-friendly operations or investments in green technologies (e.g., cleaner fuels, emission reduction systems).

Premiums are primarily risk-based without considering environmental performance.

2. *Inadequate Coverage for Environmental Risks:*

While some policies cover pollution incidents, they often lack comprehensive coverage for proactive environmental measures or green innovation.

Emerging environmental risks associated with climate change, such as rising sea levels and extreme weather events, are not fully addressed.

3. *Short-Term Focus:*

Traditional insurance models tend to focus on immediate risks and losses, rather than long-term sustainability outcomes.

This can discourage investments in innovative, green maritime technologies with uncertain or long-term benefits.

4. *Limited Integration with Green Certification or Standards:*

Standard policies do not incorporate or reward adherence to environmental standards, such as ISO 14001 or IMO's Green Shipping practices.

Lack of alignment with sustainability goals reduces motivation for green investments.

5. *High Costs for Green Technologies:*

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Insurers may view green upgrades (such as retrofitting ships with eco-friendly technology) as risky or costly, leading to higher premiums or a reluctance to insure such investments.

6. *Insufficient Data and Metrics:*

Limited data on the performance and risks associated with green maritime innovations hampers the development of tailored insurance products.

Without reliable metrics, it is challenging to assess environmental benefits and incorporate them into risk models.

7. *Limited Support for Green Financing Instruments:*

Traditional insurance does not readily support or facilitate green bonds, green loans, or other innovative financial instruments designed for sustainable maritime projects.

4.2. How Green Finance Can Address These Limitations

To better support sustainable maritime practices, innovations such as green insurance, performance-based premiums, and risk-sharing mechanisms can be developed.

These include:

1. Incentives for green investments (e.g., discounts for ships using cleaner fuels).
2. Coverage for environmental liabilities and proactive measures.
3. Integration with sustainability standards and certification schemes.
4. Data-driven risk assessment for green technologies.
5. Supporting green bonds and investments through tailored insurance products.

Traditional maritime insurance is primarily risk-based, focusing on physical damage and liabilities, with limited emphasis on environmental sustainability. Its limitations in green finance include a lack of incentives for eco-friendly practices, inadequate coverage for environmental risks, and insufficient integration with sustainability standards. Overcoming these challenges requires evolving insurance models to better align with green finance goals and fostering sustainable maritime development.

An example of a green maritime insurance product and some innovative models that are emerging to support sustainable maritime practices.

Overview:

The Green Vessel Insurance Policy is designed to incentivize and support environmentally sustainable shipping practices. It offers benefits such as reduced premiums or special coverage options for ships that meet specific green standards.

Features:

1. Premium Discounts: Ships that use cleaner fuels, implement energy-efficient technologies, or adhere to green certifications (such as the Green Ship Certification by the IMO) receive lower premiums.
2. Coverage for Green Technologies: Additional coverage options for retrofitting ships with eco-friendly systems, including scrubbers, ballast water management systems, and alternative fuel systems.
3. Environmental Liability Coverage: Extended coverage for pollution incidents or environmental damages caused by the vessel.
4. Performance-based Incentives: Premium adjustments based on environmental performance metrics, such as reduced emissions or fuel consumption.

Benefits:

- ✓ Encourages ship-owners to adopt green practices.
- ✓ Reduces environmental risks and liabilities.
- ✓ Aligns insurance with sustainability goals and regulatory compliance.

4.3. Innovative Insurance Models Supporting Green Maritime Finance

1. **Parametric Insurance for Climate Risks**:

Pays out based on predefined climate or environmental triggers (e.g., extreme weather events, rising sea levels) affecting maritime routes or infrastructure. Enables proactive risk management and supports investments in climate-resilient infrastructure.

2. **Green Bonds and Insurance Linkages**:

Insurance products designed to support green bond projects, such as financing the construction of eco-friendly ships or port infrastructure. Offers lower premiums or guarantees for projects meeting specific sustainability criteria.

3. **Performance-based Premiums and Rewards**:

Premiums are adjusted based on the vessel's environmental performance, encouraging continuous improvement. Rewards include premium reductions, reputation benefits, or access to specialized green funding.

4. **Risk-sharing and Blended Finance Models:**

Public-private partnerships where insurers, governments, and financial institutions share risks associated with green maritime investments. Helps lower barriers for innovative green projects by reducing upfront costs and risk exposure.

5. **Green Insurance Certification Programs**:

Certification schemes that recognize and validate environmentally sustainable practices in maritime

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operations, leading to better insurance terms and market recognition.

Green maritime insurance products and innovative models aim to align financial incentives with sustainability goals. They encourage the adoption of eco-friendly technologies, support climate resilience, and facilitate access to green financing instruments, such as green bonds and sustainable investments.

4.4. Funding for projects that promote environmental sustainability

The global green bond market exceeded USD 1 trillion in 2022, with a CAGR of about 30% over the past five years (Climate Bonds Initiative). Many countries have set ambitious targets for renewable energy investments, with green finance playing a crucial role in achieving these goals.

Funding for projects that promote environmental sustainability can come from various sources, including government agencies, private foundations, corporate social responsibility programs, and international organizations. Here are some common avenues to explore (Table 4).

5. HOW INSURANCE CONTRIBUTES TO GREEN & SUSTAINABLE MARITIME DEVELOPMENT

Green Insurance Products

- Insurance for environmentally friendly ships (e.g., LNG-powered vessels)
- Coverage for pollution prevention and response
- Insurance linked to sustainable practices (e.g., lower premiums for eco-friendly ships)
- Risk Management & Resilience
- Supporting investments in cleaner technologies
- Covering risks associated with new green technologies
- Encouraging Compliance & Innovation
- Incentives for adopting IMO regulations and standards
- Promoting research and development in green shipping

Detail how "green insurance products" are tailored for eco-friendly ships and projects.

Green insurance products are specialized insurance solutions designed to promote environmentally sustainable practices, particularly in the shipping industry. When tailored for eco-friendly ships and products, these insurance offerings aim to incentivize and support the adoption of greener technologies and operations. Here is how green insurance products are customized for eco-friendly ships and products:

1. Coverage for Green Technologies

Hull and machinery insurance can include coverage for new eco-friendly technologies, such as scrubbers, ballast water treatment systems, and alternative fuel engines (e.g., LNG, hydrogen).

Specialized coverage** for renewable energy ships (e.g., wind-assisted vessels, solar-powered ships) or hybrid systems.

2. Incentives for Sustainable Practices

Premium discounts or rebates for ships that meet specific environmental standards or certification programs (e.g., ISO 14001, Green Marine, Clean Shipping Index).

Bonus schemes for vessels employing low-emission fuels or innovative energy-saving technologies.

3. Coverage for Regulatory Compliance

Insurance products that help ship-owners manage risks associated with evolving environmental regulations (e.g., IMO 2020 sulphur cap, ballast water management regulations).

Coverage for fines, penalties, or liabilities arising from non-compliance with environmental laws.

4. Protection Against Environmental Liabilities

Coverage for accidental pollution or environmental damage caused by eco-friendly ships, which may have different risk profiles than traditional ships.

Liability coverage for damage caused to marine ecosystems or third parties during operations involving green ships.

5. Cargo Insurance for Green Products

Tailored policies for eco-friendly cargoes, such as sustainable goods, organic products, or renewable energy components.

Coverage for damage or loss of environmentally sensitive cargo, with considerations for special handling or storage requirements.

6. Supporting Sustainable Supply Chains

Insurance solutions that facilitate green supply chain initiatives, including insuring multi-modal transport involving eco-friendly ships.

Coverage for logistics companies prioritizing sustainable transport options.

7. Risk Management and Advisory Services

Green insurance providers often offer risk assessment services to help shipping companies identify and mitigate environmental risks.

Guidance on best practices for sustainable operations, aligning insurance coverage with environmental goals.

8. Innovative Financial Products

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Green bonds or sustainability-linked insurance policies that tie premiums or coverage terms to achieving specific environmental metrics.

Pay-as-you-save models encourage investment in eco-friendly ship upgrades.

Green insurance products for eco-friendly ships and products are designed to incentivize sustainable practices, ensure regulatory compliance, and manage specific environmental risks. They are tailored through specialized coverage options, discounts, and advisory services that support the transition to greener shipping solutions, ultimately fostering a more sustainable maritime industry.

Insurance premiums can be effectively linked to a company's sustainability performance by incorporating environmental, social, and governance (ESG) metrics into the underwriting and pricing processes. This approach incentivizes companies to adopt greener practices and improve their sustainability credentials. Here is how it works:

1. *Incorporation of ESG Metrics into Risk Assessment*
- ✓ Environmental Performance: Companies demonstrating strong environmental practices—such as reducing carbon emissions, efficient resource utilization, effective waste management, and adopting renewable energy—are perceived as lower risk.
- ✓ Social and Governance Factors: Good labor practices, community engagement, and Transparent governance also influences risk profiles.

2. *Dynamic Premium Pricing*:
- ✓ Lower Premiums for Sustainable Companies: Firms with high sustainability scores may receive discounts or lower premiums because they are viewed as less likely to face environmental liabilities, regulatory penalties, or reputational damage.
- ✓ *Higher Premiums for Poor Performers*: Conversely, companies with poor sustainability records or higher environmental risks may face increased premiums to compensate the insurer for the elevated risk.

3. *Use of Sustainability Certification and Reporting* - Insurers can require companies to submit sustainability reports, third-party certifications (e.g., ISO 14001), or ESG ratings from recognized agencies. Premium discounts can be granted based on these verified credentials.

4. *Risk Reduction Incentives*
- ✓ Premium Discounts for Risk Mitigation: Companies that invest in greener technologies, energy efficiency upgrades, or pollution controls may be eligible for lower premiums.
- ✓ *Premium Penalties for Negative Practices*: Companies engaging in environmentally harmful activities or lacking sustainability measures may incur higher premiums

5. *Promoting Sustainable Practices*: By linking premiums to sustainability, insurers incentivize companies to:
- ✓ Reduce environmental impact
- ✓ Improve resource efficiency
- ✓ Adopt sustainable supply chain practices
- ✓ Enhance overall ESG performance

6. *Impact and Benefits*
- ✓ For Companies: Cost savings through reduced premiums and improved reputation.
- ✓ For Insurers: Lower claims risk, enhanced portfolio resilience, and alignment with global sustainability goals.
- ✓ For Society: Encouragement of greener practices that contribute to environmental protection and climate change mitigation.

- **Example**

Some insurers offer premiums discounted up to 10-15% for ships that meet specific environmental standards. Examples include coverage for LNG-powered vessels, which emit 20-25% less CO2 than traditional ships.

A manufacturing company that invests in renewable energy, reduces waste, and maintains high safety and labour standards might receive a premium discount. Conversely, a company with poor environmental compliance and high pollution levels may face higher premiums, creating a financial incentive to improve its practices.

In summary, **linking insurance premiums to a company's sustainability performance** creates a financial incentive for greener practices, aligning corporate behaviour with broader environmental and social goals while also managing insurer risk more effectively.

- ***Case Studies & Examples***
- ✓ Green insurance initiatives in the maritime sector
- ✓ Successful implementation of sustainable shipping projects
- ✓ Insurance companies leading in green maritime insurance products

Here are some real-world examples where insurance companies have supported or promoted green initiatives, including Lloyd's of London and other insurers backing sustainable practices:

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1. Lloyd's of London and Sustainable Shipping Initiatives

Lloyd's of London, one of the world's most prominent insurance marketplaces, has been actively involved in promoting sustainable shipping practices. Lloyd's has launched specific insurance products for zero-emission ships, with some policies offering premium reductions of up to 20% for compliant vessels.

- ✓ Sustainable Shipping Insurance & Green Finance: Lloyd's has partnered with industry stakeholders to develop insurance products that incentivize the adoption of greener shipping technologies. They support projects that reduce carbon emissions, such as retrofitting ships with cleaner engines or using alternative fuels.
- ✓ Lloyd's Green Shipping Program: Lloyd's has launched initiatives to underwrite ships that meet environmental standards, such as those complying with the International Maritime Organization's (IMO) greenhouse gas reduction targets. They encourage ship-owners to adopt energy-efficient designs and renewable fuel sources by offering favorable insurance terms.
- ✓ Partnerships with Maritime Innovations: Lloyd's collaborates with organizations such as the Marine Environment Protection Committee (MEPC) and supports startups developing sustainable maritime technologies, including zero-emission vessels, by providing tailored insurance solutions.

2. Sailors for the Sea (Sustainable Marine Initiative) & Insurance Support

Sailors for the Sea is a non-profit organization dedicated to promoting ocean conservation through sailing and marine activities. While they are not an insurer, some insurance firms have supported their initiatives:

- ✓ Insurance Companies Supporting Ocean Conservation:* Certain marine insurance providers, such as *The North of England P&I Association* or *AIG**, have sponsored or partnered with Sailors for the Sea to promote sustainable sailing practices, marine protected areas, and reduce pollution.
- ✓ Coverage for Eco-Friendly Vessels:** Some insurers provide specialized coverage for eco-friendly vessels and sustainable maritime projects, incentivizing operators to adopt greener technologies.

3. AXA and Green Investment Bonds

AXA's Climate and Green Bonds: AXA and other insurers have issued or invested in green bonds that fund renewable energy projects, sustainable infrastructure, and environmentally friendly shipping initiatives, demonstrating their commitment to sustainability.

4. MS Amlin and Sustainable Insurance Solutions

MS Amlin, a global insurer, has developed products that support renewable energy projects, including offshore wind farms and sustainable shipping. They offer tailored coverage for vessels using alternative fuels or zero-emission technologies, incentivizing cleaner shipping methods.

The Green Ship of the Year Award (by various maritime bodies) recognizes ships with innovative green solutions often backed by specialized insurance.

As shown, Lloyd's of London actively promotes sustainable shipping through specialized insurance products and partnerships. Marine insurance providers support eco-friendly vessels by retrofitting ships with greener technology and investing in sustainable maritime projects. Non-profit organizations, such as Sailors for the Sea, collaborate with insurers to promote ocean conservation and sustainable marine practices.

The Impact - These examples demonstrate how insurance companies are not only passively covering risks but also actively promoting environmental sustainability by incentivizing greener practices, funding innovation, and collaborating with stakeholders to protect marine environments and reduce carbon footprints in the shipping and maritime industries.

Here are some notable success stories of ships using alternative fuels or upgraded reduction technology, which have benefited from favourable insurance rates due to their improved safety and environmental performance (Table 5).

Key Factors for Favourable Insurance Rates:

- ✓ Environmental Compliance: Ships that meet or exceed regulatory standards tend to receive better rates.
- ✓ Enhanced Safety Features: Upgraded technology often improves safety, reducing accident risk.
- ✓ Operational Experience: Proven performance with alternative fuels or tech upgrades builds insurer confidence.
- ✓ Risk Management: Ships with better safety records and environmental performance are considered lower risk.

The shipping industry's shift toward cleaner fuels and advanced emission reduction technologies is not only environmentally beneficial but also financially advantageous, as it results in lower insurance premiums. These success stories serve as models for future adoption, highlighting the importance of technological innovation in maritime safety and sustainability.

6. CHALLENGES & OPPORTUNITIES

- **Challenges in Green Finance**

1. *Lack of Standardization and Transparency*

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- ✓ Lack of standardized metrics for measuring green performance. Difficulty in establishing a universally
- ✓ accepted standards for green assets and investments.
- ✓ Risk of greenwashing, where projects are falsely marketed as environmentally friendly
- ✓ Limited awareness and understanding

2. *Limited Access to Capital*

- ✓ Smaller or emerging markets may face difficulties in attracting sufficient investment.
- ✓ High upfront costs of green technology and perceived risks deter private sector participation.

3. *Data Gaps and Quality*

- ✓ Limited availability of reliable data on environmental impacts.
- ✓ Challenges in Measuring and Verifying Sustainability Claims.

4. *Policy and Regulatory Uncertainty*

- ✓ Inconsistent policies across jurisdictions can hinder investment.
- ✓ Changes in regulations can create unpredictability for investors.

5. *Technological Risks and Innovation Barriers*

- ✓ Uncertainty around the performance and scalability of new green technologies.
- ✓ High R&D costs and longtime horizons can inhibit innovation.

Emphasize opportunities such as the growth of green finance markets, technological advancements, and supportive policies.

Green shipping investments are expected to reach USD 10 billion annually by 2030 (Maritime Green Finance Report 2022). The cost of retrofitting ships with eco-friendly technology can be two to five times higher than traditional upgrades.

Green finance is an evolving sector that plays a crucial role in transitioning toward a sustainable and low-carbon economy. Here is an overview of the key challenges and opportunities related to green finance, focusing on market growth, technological advances, and supportive policies:

- **Opportunities in Green Finance**

1. *Growing Green Finance Markets* (Growing market for green insurance products)

- ✓ Increasing issuance of green bonds, green loans, and ESG (Environmental, Social, and Governance) funds.
- ✓ Rising investor demand for sustainable investment products.
- ✓ Expanding markets in renewable energy, energy efficiency, and sustainable infrastructure.

2. *Technological Advances*

- ✓ Innovations in clean energy, electric vehicles, smart grids, and carbon capture and storage.
- ✓ Use of big data, AI, and block-chain to improve transparency, monitoring, and verification.
- ✓ Development of new financial instruments such as sustainability-linked bonds and climate insurance.

3. *Supportive Policies and Regulatory Frameworks* (Policy support and international cooperation)

- ✓ Governments and international bodies are adopting climate commitments (e.g., Paris Agreement).
- ✓ Implementation of tax incentives, subsidies, and regulatory mandates for green investments.
- ✓ Integration of sustainability criteria into financial regulations and reporting standards (e.g., EU taxonomy).

4. *Increased Private Sector Engagement*

- ✓ Corporate commitments to sustainability goals.
- ✓ Integration of ESG factors into mainstream investment decision-making.
- ✓ Development of innovative financing solutions tailored to green projects.

5. *Global Collaboration and Funding*

- ✓ Multilateral initiatives (e.g., Green Climate Fund) provide concessional finance.
- ✓ Cross-border investments facilitate technology transfer and capacity building.
- ✓ Potential for significant environmental and economic benefit

Challenges include standardization issues, data gaps, policy uncertainty, technological risks, and limited access to capital.

Opportunities include market expansion, technological innovation, supportive policies, private sector engagement, and international cooperation. Stress the importance of collaboration among stakeholders, including governments, insurers, ship owners, and financiers.

- **Policy Recommendations on Green Finance and Maritime Insurance for Sustainable Maritime Development**

1. Establishing Robust Green Financing Frameworks

- ✓ Develop dedicated green financing instruments such as green bonds, sustainability-linked loans, and maritime-specific green funds to channel investments into sustainable maritime projects.
- ✓ Incentivize private sector participation through tax benefits, subsidies, or risk guarantees for investments in environmentally friendly maritime infrastructure, vessels, and technologies.

2. Integrating Environmental, Social, and Governance (ESG) Criteria

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- ✓ Mandate ESG disclosures for maritime companies, financial institutions, and insurers to promote transparency and accountability.
- ✓ Incorporate ESG risk assessments into lending and investment decision-making processes to encourage sustainable practices.

3. Aligning Financial Mechanisms with Maritime Sustainable Development Goals

- ✓ Align existing financial instruments with the targets of SMDGs, such as reducing maritime pollution, increasing energy efficiency, and promoting clean shipping.
- ✓ Develop sector-specific sustainability standards for maritime finance and insurance, ensuring that investments support low-carbon and resilient maritime infrastructure.

4. Enhancing Maritime Insurance for Sustainability

- ✓ Develop innovative insurance products that incentivize sustainable practices, such as offering lower premiums to vessels that adhere to green standards or retrofit older ships with cleaner technologies.
- ✓ Introduce climate risk coverage tailored for maritime assets vulnerable to climate change impacts, including rising sea levels and extreme weather events.

5. Strengthening Regulatory and Policy Frameworks

- ✓ Implement policies and regulations that promote the adoption of green technologies in maritime operations, such as sulfur emission limits and ballast water management.
- ✓ Facilitate public-private partnerships** to mobilize investment in sustainable maritime infrastructure and innovation.

6. Promoting Capacity Building and Knowledge Sharing

- ✓ Support training programs for financial institutions, insurers, and maritime stakeholders on sustainable finance principles.
- ✓ Create platforms for knowledge exchange on best practices, emerging technologies, and innovative financial products in the maritime sector.

7. Leveraging International Cooperation and Funding

- ✓ Participate in global initiatives and funding mechanisms (e.g., Green Climate Fund, Global Environment Facility) to access financial support for sustainable maritime projects.
- ✓ Coordinate cross-border efforts to develop regional standards and policies aligned with SDGs.

8. Monitoring and Reporting

- ✓ Establish monitoring frameworks to track progress toward sustainability targets in the maritime finance and insurance sectors.
- ✓ Encourage transparent reporting on environmental performance and financial impacts to foster trust and accountability.

- **Future Prospects**

1. **Growing Market for Green Maritime Finance**: Increasing investor awareness and regulatory pressure are likely to expand the market for green bonds, loans, and insurance products tailored to the maritime sector.
2. **Technological Innovation:** Advances in clean propulsion, digitalization, and data analytics will facilitate smarter, more sustainable maritime operations.
3. **Enhanced Resilience and Risk Management:** Climate-proof insurance products will become essential as climate risks intensify.
4. **Policy and Regulatory Developments**: Stricter international standards (e.g., IMO regulations) will catalyze shifts toward greener maritime practices.

Aligning financial mechanisms and maritime insurance with sustainable maritime development requires a comprehensive approach that combines regulatory reforms, innovative financial products, capacity building, and international cooperation. This alignment not only supports environmental sustainability but also enhances economic resilience and competitiveness in the maritime sector.

6. CONCLUSIONS

In summary**,** green finance is a vital tool for mobilizing the capital needed to address environmental challenges and promote sustainable development, thereby ensuring a healthier planet and an improved quality of life for future generations.

The transformative potential of innovative green financial products and insurance solutions

In recent years, the urgency to combat climate change and promote sustainable development has accelerated the need for innovative financial tools. Green finance—comprising financial products and insurance solutions designed to support environmentally friendly initiatives—has become a cornerstone in transitioning to a more sustainable economy. The transformative potential of these innovations lies in their ability to mobilize capital, manage environmental risks, and foster a culture of sustainability across sectors.

1. Mobilizing Capital for Sustainability

Innovative green financial products, such as green bonds, sustainability-linked loans, and green funds, are designed to channel private and public capital into environmentally beneficial projects. These products offer attractive returns while ensuring that investments contribute to climate mitigation, renewable energy deployment, and resource conservation. Their transformative power is evident in:

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- ✓ Scaling up investments in renewable energy, energy efficiency, and sustainable infrastructure.
- ✓ Attracting a broader investor base, including institutional investors and retail investors who prioritize ESG (Environmental, Social, and Governance) criteria.
- ✓ Facilitating access to capital for projects that might otherwise face funding barriers due to perceived risks or high initial costs.

2. Innovative Insurance Solutions for Climate Risks

Climate change introduces unprecedented risks—extreme weather events, rising sea levels, and supply chain disruptions—that pose significant threats to businesses and communities. Innovative insurance solutions are evolving to address these challenges:

- ✓ Parametric insurance, which pays out based on predefined triggers (like a hurricane reaching a certain wind speed), provides rapid relief.
- ✓ Climate risk insurance tailored for vulnerable sectors, such as agriculture and fisheries, helps mitigate the financial impact of climate-related disasters.
- ✓ Insurance-linked securities (ILS) and catastrophe bonds transfer risks from insurers to capital markets, increasing resilience and capacity to cover climate-related losses.

These solutions are transformative because they:

- ✓ Enhance the resilience of communities and businesses against climate shocks.
- ✓ Encourage proactive risk management and climate adaptation.
- ✓ Reduce the financial burden on governments and societies in disaster recovery.

3. Driving Innovation and Market Development

- ✓ The development of green financial products stimulates innovation within the financial sector:
- ✓ New financial instruments are created to meet the specific needs of green projects.
- ✓ Standardization and certification frameworks, such as the Green Bond Principles or Climate Bonds Standard, increase transparency and credibility.
- ✓ The integration of technology, such as block chain and AI, enhances transparency, tracking, and reporting of green investments.

This innovation accelerates the mainstream adoption of sustainability principles, transforming traditional finance into a driver for environmental and social progress.

4. Facilitating Policy and Regulatory Support

Governments and regulators are increasingly supporting green finance through policies, incentives, and regulations:

- ✓ Tax incentives, subsidies, and mandates encourage the issuance of green bonds and sustainable insurance products.
- ✓ Mandatory ESG disclosures increase transparency and investor confidence.
- ✓ Public-private partnerships utilize private capital to fund large-scale green infrastructure projects.

Such supportive frameworks amplify the transformative impact of green financial innovations.

5. Creating a Sustainable Economic Model

Ultimately, the transformative impact of these financial products and insurance solutions lies in their ability to:

- ✓ Align economic incentives with environmental sustainability.
- ✓ Foster a circular economy by funding renewable energy, waste reduction, and sustainable resource management.
- ✓ Promote social equity by ensuring that vulnerable communities benefit from green investments and insurance coverage.

The transformative nature of innovative green financial products and insurance solutions is reshaping the flow of capital into sustainable development. By mobilizing resources, managing climate risks, and fostering innovation, these financial tools play a crucial role in building a resilient, low-carbon, and inclusive economy. Their continued evolution and adoption are critical to achieving global climate and sustainability goals.

Call to action for stakeholders to embrace sustainable practices.

As stewards of our planet's future, it is imperative that we—business leaders, investors, policymakers, and communities—act decisively to prioritize sustainability. Green finance and innovative insurance solutions are powerful tools that can accelerate our transition toward a resilient, low-carbon economy.

We urge all stakeholders to:

- ✓ **Invest in Green Initiatives**:

Channel capital into renewable energy, sustainable infrastructure, and eco-friendly projects that generate long-term value and environmental benefits.

- ✓ **Integrate ESG Principles**:

Embed environmental and social considerations into decision-making processes to promote responsible growth.

- ✓ **Innovate and Adopt Green Financial Products**:

Support the development and utilization of green bonds, sustainability-linked loans, and climate risk insurance to fund and safeguard sustainable ventures.

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✓ **Advocate for Supportive Policies**:
Push for regulatory frameworks, incentives, and standards that encourage green investments and transparent reporting.

✓ **Collaborate Across Sectors**:
Foster partnerships among governments, financial institutions, businesses, and civil society to scale sustainable solutions.

✓ **Drive Behavioral Change**:
Promote awareness and education on the importance of sustainability, inspiring action at every level.

Together, we can harness the transformative power of green finance and insurance to protect our environment, empower communities, and ensure a prosperous, sustainable future for generations to come. The time to act is now—let us lead the change!

Table 3. Case studies of green finance applications in maritime projects

Item	Overview:	Key Initiatives Funded	Impact	Significance
The Green Bond for the Port of Rotter-dam (Nether-lands)	The Port of Rotterdam, one of the largest ports in Europe, issued a green bond in 2016 to fund sustainable infrastructure and environmental initiatives. The bond raised €300 million to support projects aimed at reducing carbon emissions and enhancing port sustainability.	Electrification of port terminals and ships Development of renewable energy sources (solar and wind) Implementation of green logistics and transportation solutions	Significant reduction in port-related emissions Increased investment in sustainable maritime infrastructure Enhanced port competitiveness and environmental performance	This case exemplifies how green bonds can mobilize private capital for large-scale maritime sustainability projects, fostering innovation and environmental responsibility in port operations.
The Green Shipping Program – The Maritime Green Investment Fund (Norway)	Norway launched a Green Shipping Investment Fund to support the transition to low-emission shipping vessels, including LNG-powered ships and hybrid vessels. The fund attracted private investments through public guarantees and subsidies.	Funded: Construction of eco-friendly ships Retrofitting existing vessels with cleaner technologies Developing shore power infrastructure at ports	Reduction of greenhouse gases and sulphur emissions Demonstration of commercially viable green shipping technologies Encouragement of industry-wide adoption of sustainable practices	This case illustrates how targeted green finance, coupled with government support, can accelerate the adoption of cleaner maritime technologies and mitigate the sector's environmental impact.
The Green Maritime Methanol Project (Singapore)	Singapore's Maritime and Port Authority (MPA) partnered with industry stakeholders to finance the development of methanol-powered ships. The project received funding through a mix of government grants and private investment, aiming to demonstrate the viability of alternative fuels.	Design and construction of methanol-powered vessels Building supply chains for green methanol Infrastructure development at ports for fuel bunkering	Pioneering use of renewable methanol as a maritime fuel Reduction of carbon emissions and sulphur oxides Positioning Singapore as a leader in clean maritime fuels	This demonstrates how innovative green finance can facilitate the transition to alternative fuels in shipping, addressing climate and air quality concerns
The European Investment Bank (EIB) Financing for Sustainable Maritime Infrastructure	The EIB has provided multiple loans and grants to European ports and maritime infrastructure projects that emphasize sustainability, including investments in renewable energy, electrification, and cleaner vessel technologies.	Electrification of port cranes and vehicles Development of shore power facilities Support for maritime research and innovation projects	Reduced emissions from port operations Enhanced energy efficiency Stimulated green innovation in maritime logistics	This case highlights the crucial role of multilateral financial institutions in fostering sustainable maritime infrastructure through concessional and strategic financing.

Table 4. Various sources of funding for projects

Source of Funds	Name of Agencies	Grants provided

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Government Grants and Programs	- Environmental Protection Agency (EPA) (U.S.) - National Science Foundation (NSF) - Department of Energy (DOE) - European Union Funding	-Offers grants for sustainability, conservation, and pollution reduction projects. -Funds research and innovation in environmental science and sustainability. -Supports renewable energy and energy efficiency initiatives - Programs like Horizon Europe support sustainability projects across member states.
Private Foundations and Non-profits	The Bill & Melinda Gates Foundation The Rockefeller Foundation The Ford Foundation	Occasionally, fund environmental sustainability initiatives. Supports resilient cities and sustainable development. Focuses on social justice with some projects related to environmental sustainability.
Corporate Social Responsibility (CSR) Initiatives	Many corporations have CSR programs that fund sustainability projects, particularly in renewable energy, waste reduction, or community resilience initiatives.	
International Organizations	United Nations Development Programme (UNDP) World Bank Global Environment Facility (GEF)	Funds projects aligned with sustainable development goals (SDGs). Provides funding for large-scale environmentalists in developing countries. Supports projects that address biodiversity, climate change, and sustainable land management.

Table 5. Notable success stories of ships

Ships Success Stories	Overview	Success	Insurance Benefits
Maersk's Use of Green Methanol	Maersk, one of the world's largest shipping companies, has been pioneering the adoption of green methanol as an alternative fuel.	The Maersk Eco Clipper, a container vessel powered by methanol, has demonstrated significant reductions in greenhouse gas emissions—up to 80% compared to conventional fuels.	Due to their lower environmental risk profile and compliance with emerging emission standards, vessels like these have been able to negotiate more favourable insurance premiums with insurers who are increasingly incentivized to support greener fleets.
Wärtsilä Hybrid and LNG-Powered Vessels	Wärtsilä has developed hybrid propulsion systems and LNG-powered ships that significantly reduce emissions of NOx, SOx, and particulate matter.	Several ferries and offshore support vessels equipped with Wärtsilä's hybrid and LNG systems have achieved operational excellence, with enhanced safety records and lower operational costs.	These vessels often benefit from reduced premiums due to their enhanced safety features, compliance with strict emission regulations, and lower risk of environmental accidents.
Zero-Emission LNG Ferries in Scandinavia	Norway and Sweden have introduced LNG-fuelled ferries for passenger and cargo transport.	The *Stavanger-fjord* and other LNG ferries have successfully operated with minimal emissions, and their adoption has facilitated access to insurance discounts due to their environmentally friendly profile.	Favourable Rates: - Insurers have offered reduced premiums owing to the lower risk of pollution incidents and the vessel's compliance with strict environmental standards.
Upgraded Reduction Technology in Bulk Carriers	Several bulk carriers have upgraded their exhaust gas cleaning systems (scrubbers) and installed advanced emission reduction technology.	:* Ships like the *Golden Odyssey** have achieved compliance with IMO Tier III standards, reducing sulphur emissions and improving operational safety	These upgrades have contributed to lower premiums, as insurers recognize the reduced risk of regulatory penalties and environmental liabilities.

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7. CREdit authors statement

Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing – original draft; Writing – review & editing: A.M. B.; V;M R.S..

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BRIDGING AMATEUR METEOROLOGY AND HURRICANE MONITORING: A PORTABLE WEATHER MONITORING SYSTEM FOR ISLAND COMMUNITIES

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Abstract: Hurricanes are extreme meteorological events with significant consequences for island communities, where geographical isolation, exposure to strong winds, and infrastructure vulnerability can intensify their social and operational impacts. In this context, real-time local weather monitoring can support preparedness, situational awareness, and emergency response. This study presents the design, implementation, and functional evaluation of a portable, low-cost meteorological monitoring system intended for hurricane-prone island environments. The prototype measures wind speed, temperature, relative humidity, and atmospheric pressure using a Hall sensor-based cup anemometer and an integrated AHT20 + BMP280 sensor module. The collected data are transmitted wirelessly to a central station and published online through the ThingSpeak platform, enabling remote access and visualisation. The system architecture, operating principles, and communication flow are described to show how localised meteorological data can be acquired and made available remotely. Functional tests confirmed the prototype's ability to collect, transmit, and publish meteorological data, indicating its potential as a complementary tool for local weather observation in areas exposed to severe weather events.

Key words: hurricane-prone islands; disaster preparedness; portable weather station; low-cost meteorological instrumentation; remote data visualisation.

1. INTRODUCTION

Tropical cyclones (TCs), referred to as hurricanes in the Atlantic and eastern North Pacific basins, are among the most destructive meteorological hazards, affecting millions of people worldwide each year [1, 2]. In these basins, a tropical cyclone is classified as a hurricane when its maximum sustained winds reach at least 64 knots, equivalent to approximately 119 km/h or 74 mph [3]. Hurricane intensity is commonly described using the Saffir-Simpson Hurricane Wind Scale, which relates wind-speed categories to the potential for property damage and infrastructure disruption [4]. Beyond extreme winds, tropical cyclones are multi-hazard events that may produce torrential rainfall, storm surges, flooding, and occasionally tornadoes, generating complex impacts on natural and human systems [2].

Island areas are particularly exposed to the effects of hurricanes because geographical isolation, limited land area, and dependence on critical infrastructure can increase vulnerability. Ports, airports, coastal roads, electricity networks, and communication systems are essential for evacuation, emergency response, and recovery, but they may also be severely affected during extreme weather events. In small island contexts, damage to a limited number of critical assets can disrupt emergency coordination and post-event recovery [8, 9].

Meteorological observation is a key component of early warning systems. The World Meteorological Organization identifies detection, monitoring, analysis, and forecasting as essential elements of effective multi-hazard early warning, together with risk knowledge, warning dissemination, and preparedness to respond [5]. At the global scale, observing systems support weather analyses, forecasts, advisories, warnings, and climate monitoring [6]. However, in isolated or resource-limited island environments, local observations may be spatially sparse or difficult to maintain, especially during severe weather events.

The atmospheric parameters selected for monitoring in this study are directly relevant to hurricane-prone environments. Wind speed is one of the defining characteristics of hurricane intensity and is essential for evaluating hazardous wind conditions. Atmospheric pressure variations may indicate the approach or development of low-pressure weather systems, while

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temperature and relative humidity contribute to the characterisation of local atmospheric conditions. These variables are consistent with WMO guidance on meteorological observation, including air temperature, atmospheric pressure, humidity, surface wind, and automatic weather stations [7].

Recent developments in embedded systems, wireless communication, and Internet of Things technologies have enabled compact and affordable weather stations for real-time environmental monitoring. Such systems do not replace certified meteorological stations, but they can provide useful supplementary observations for educational, research, community-based, or temporary field applications [10]. In this context, the term amateur meteorology refers to non-certified, community-oriented, and low-cost observation activities that can complement, but not replace, official meteorological infrastructure.

The aim of this paper is to present and functionally evaluate a portable, low-cost meteorological monitoring system designed to complement local weather observations and support situational awareness in hurricane-prone island environments.

2. MONITORING NEEDS IN HURRICANE-PRONE ISLAND ENVIRONMENTS

Hurricane-prone island environments require monitoring approaches capable of providing timely, localised, and accessible meteorological information. The IPCC reports that small islands are increasingly affected by tropical cyclones, storm surges, heavy precipitation, sea-level rise, and related impacts across natural and human systems [8]. Studies on Small Island Developing States also show that disaster vulnerability results from the interaction between physical exposure and local social, economic, and institutional conditions [9].

Although global and national observing networks provide indispensable information for forecasting and warning [5, 6, 7], local observations may be sparse in isolated or underserved areas, especially in small island contexts where exposure, remoteness, and infrastructure limitations increase vulnerability [8, 9]. During severe weather events, permanent monitoring infrastructure may also be affected by power outages, communication disruptions, flooding, corrosion, or physical damage [5, 8, 9]. Complementary local monitoring systems can therefore add practical value by increasing the number of observation points in vulnerable or underserved locations [5, 10].

For a local monitoring system to be useful, it should acquire relevant atmospheric variables and make them available to users without requiring direct access to the instrument. Wind speed, atmospheric pressure, temperature, and relative humidity provide a basic but important picture of the local atmospheric state and are among the standard variables considered in meteorological observation practice [7]. Remote visualisation further supports situational awareness because users can observe changing conditions from a safer or more centralised location, which is consistent with the role of timely observation and communication in early warning systems and IoT-based monitoring approaches [5, 10].

In this paper, this monitoring need is addressed through a portable weather station designed to acquire wind speed, temperature, relative humidity, and atmospheric pressure data and publish them online. The system is intended as a complementary observation tool rather than an official source for warnings, certified measurements, or safety-critical decisions.

3. DESIGN AND IMPLEMENTATION OF THE PORTABLE WEATHER STATION

The proposed system was designed as a two-node architecture consisting of a portable measurement unit and a central receiving station. The measurement unit acquires local meteorological data, while the central station receives the data through a wireless link and publishes them online. The general data flow is presented in Figure 1.



Figure 1 General architecture of the portable meteorological monitoring system

The portable unit is controlled by an ESP32 development board, selected because it provides sufficient processing capability for sensor reading, pulse counting, local display, and wireless communication in a compact format. In the documented prototype configuration, temperature and relative humidity are acquired using an AHT20 sensor, while atmospheric pressure is measured using a BMP280 module. The measured values are also shown on a small OLED display, which allows direct verification during testing and deployment.

Wind speed is measured using a custom cup anemometer. The rotating assembly includes three neodymium magnets placed at a constant distance from the centre of the shaft, while a KY-003 Hall-effect sensor module is fixed nearby. When the cups rotate, each magnet passes in front of the Hall sensor and generates a digital pulse. The ESP32 counts these pulses

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during the sampling interval and converts pulse frequency into a wind-speed value. At firmware level, the pulse frequency is converted into rotor speed using the configured number of pulses per revolution, after which the anemometer circumference and a provisional calibration factor are used to estimate wind speed. Since the relationship between rotor speed and actual wind speed depends on the anemometer geometry, the conversion algorithm is treated as a provisional functional implementation and requires calibration against a reference anemometer according to accepted meteorological measurement practice [7].

Wireless communication between the portable unit and the central station is currently implemented using nRF24L01 radio modules. The measurement unit sends the acquired values as data packets, while the receiving ESP32 decodes the information and prepares it for online publication. This communication solution was selected for the functional prototype because it is compact, low-cost, and suitable for short-range wireless data transmission, which is consistent with the use of low-cost components in IoT-based weather station prototypes [10]. Future versions could use SX1278 LoRa modules or ESP32 boards equipped with LoRa transceivers where longer communication range is required.

The central station is built around a second ESP32 board connected to Wi-Fi. After receiving the values from the portable unit, it publishes the data to a dedicated ThingSpeak channel using the platform API. In the tested firmware, measurements were published at 15 s intervals, which was sufficient for remote visualisation during the functional evaluation. This arrangement separates local measurement from internet publication, allowing the portable station to be placed in the monitored area while the central station manages Wi-Fi connectivity and online data visualisation.

The portable unit is powered by two 18650 lithium-ion cells connected in series and protected by a battery management module. DC-DC converters provide the voltage levels required by the electronic modules, including a 3.3 V rail for low-voltage components and a 5 V line for the ESP32 development board. The enclosure, anemometer arms, and hub were manufactured using 3D-printed PETG parts. The front panel is made of plexiglass and fitted with a silicone gasket, while a second silicone gasket is placed between the external sensor pod and the main case to improve sealing at this interface. Cable and component ingresses were sealed using hot-melt adhesive for prototype-level protection. The modular structure of the system also allows future adaptation for different monitoring objectives by changing or extending the sensor set, communication module, or enclosure design without modifying the general architecture of the prototype.

4. FUNCTIONAL EVALUATION AND RESULTS

The prototype was evaluated through functional tests intended to verify the complete data chain, from local measurement to online visualisation. The purpose of this stage was not to perform metrological calibration against certified instruments, but to confirm that the system can acquire data from the sensors, process the anemometer pulses, transmit the measurements wirelessly, and publish the results online. Formal meteorological measurement quality requires calibration, documented observing methods, and comparison with appropriate reference instruments [7].

During testing, the portable unit was powered from the 18650 battery pack and the measured values were displayed locally on the OLED screen. The AHT20 sensor was used to acquire temperature and relative humidity, while the BMP280 module provided pressure readings, which were converted in the firmware to sea-level equivalent pressure using a hard-coded altitude value. The cup anemometer was checked by rotating the rotor and observing the response of the Hall-effect sensor. Each passage of the magnets in front of the KY-003 module generated pulses that were counted by the ESP32 and converted by the software into a provisional wind-speed value.

The wireless communication link was tested using the nRF24L01 modules installed on the portable unit and on the central station. The measurement unit transmitted data packets containing the acquired meteorological values, while the receiving ESP32 decoded the information and forwarded it through Wi-Fi to the dedicated ThingSpeak channel. The online interface displayed separate charts for relative humidity, temperature, sea-level pressure, and wind speed, confirming that the measured data could be accessed remotely, as shown in Figure 2.



Figure 2 ThingSpeak dashboard during functional testing

The results confirm the functional operation of the prototype as an integrated portable weather station. The system was able to collect meteorological data, transmit them from the portable unit to the central station, and publish them online at 15 s intervals during testing. The local OLED display also allowed direct monitoring of

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the measured values during operation, which is useful during testing and field deployment. Since the evaluation did not include comparison with calibrated reference instruments, numerical accuracy indicators such as measurement error, uncertainty, or deviation from reference values are not reported at this stage.

Several limitations were identified during this stage. First, the wind-speed conversion method has not yet been calibrated against a reference anemometer. The pressure correction also depends on the accuracy of the altitude value used in the firmware. Secondly, the tests focused on functional operation rather than long-term reliability, communication range, battery autonomy, or resistance to severe outdoor conditions. Although the PETG enclosure, plexiglass front panel, silicone gasket, and sealed ingresses provide adequate levels of protection, further improvements would be required before deployment in harsh hurricane-prone island environments, where exposure to extreme weather and infrastructure vulnerability are important concerns [8, 9].

5. CONCLUSIONS AND FUTURE DEVELOPMENTS

This paper presented the design, implementation, and functional evaluation of a portable meteorological monitoring system intended for hurricane-prone island environments. The prototype was developed as a low-cost weather station capable of measuring wind speed, temperature, relative humidity, and atmospheric pressure. The system combines an ESP32-based measurement unit, a custom Hall-effect cup anemometer, an AHT20 + BMP280 sensor configuration, wireless transmission through nRF24L01 modules, and an ESP32-based central station connected to ThingSpeak for remote data visualisation.

The functional evaluation confirmed that the prototype can acquire meteorological data, display the values locally, transmit them wirelessly to the central station, and publish them online. These results demonstrate the correct operation of the main data chain, from sensor acquisition to remote visualisation. In this form, the system can be considered a practical complementary tool for local weather observation, especially in areas where permanent meteorological infrastructure is limited, difficult to access, or vulnerable during severe weather events [5, 8, 9].

At the same time, the prototype should not be regarded as a replacement for certified meteorological stations, since the current tests focused on functional operation rather than metrological accuracy, long-term reliability, or performance under extreme environmental conditions [7]. In particular, the wind-speed measurement algorithm requires calibration against a reference anemometer, and the temperature, humidity, and pressure readings should be compared with reference instruments.

Future developments will focus on improving measurement performance, mechanical robustness, autonomy, and communication range. The wind-speed measurement system could be improved through a more rigid and better aligned shaft assembly, lower-friction bearings, improved rotor balancing, more precise magnet positioning, and calibration against a reference anemometer. The enclosure could also be improved through better sealing, corrosion-resistant connectors, cable glands, and extended outdoor testing under rain, salt-air, wind, and temperature variations.

The same modular platform could also be adapted for additional sensing applications. Depending on the use case, future versions could integrate air-quality sensors, ultraviolet radiation sensors, rain detection or rainfall measurement, soil-moisture sensors, battery-voltage monitoring, local data storage, or configurable alert thresholds. These extensions would allow the prototype to be used not only for hurricane-related monitoring, but also for broader environmental observation, educational fieldwork, temporary deployments, agricultural monitoring, or community-level situational awareness.

Although the prototype was developed for hurricane-prone island environments, the same communication concept could be extended to other isolated or difficult-to-access locations, such as remote maritime worksites, offshore facilities, natural or artificial islands, temporary field stations, or areas where direct access to mainland infrastructure is limited. In such scenarios, longer-range radio modules such as SX1278, SX1262, or RFM96, possibly combined with intermediate relay nodes, would be more suitable than the short-range nRF24L01 link used in the current prototype.

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7. PROJECT MATERIALS

The firmware, documentation, and 3D-printable parts are available through the project repository: https://github.com/calinemanuelsebastian/portable-hurricane-weather-station.

8. CREdit authors statement

Conceptualization: C.E.-S., B.A.L.; Data curation: C.E.-S.; Formal analysis: C.E.-S.; Funding acquisition: not

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applicable; Investigation: C.E.-S.; Methodology: C.E.-S., B.A.L.; Project administration: B.A.L.; Resources: C.E.-S.; Software: C.E.-S.; Supervision: B.A.L.; Validation: C.E.-S., B.A.L.; Visualization: C.E.-S.; Writing – original draft: C.E.-S.; Writing – review & editing: C.E.-S., B.A.L..

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RESILIENT HYBRID RADIO COMMUNICATION NETWORK USING RADIO RELAY LINKS AND TROPOSCATTER LINKS WITH FAILOVER MECHANISMS

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Abstract: The paper presents the design and simulation of a hybrid microwave radio communication network based on the integration of radio relay and troposcatter links, aimed at ensuring communication continuity under various propagation conditions. Radio relay systems provide high capacity and low latency but require line-of-sight (LoS), while troposcatter links enable long-distance communication without LoS, at the cost of lower capacity. A hybrid architecture was adopted, where radio relay links serve as primary paths and troposcatter links act as backup. The link simulations were carried out using HTZ Warfare software. A redundant network was implemented using OSPF dynamic routing, configured to prioritize primary links and enable automatic failover. The results confirm the effectiveness of the proposed solution in ensuring reliable and robust communications for military applications.
Key words: microwave communications, troposcatter systems, dynamic routing, OSPF, network redundancy, failover.

1. INTRODUCTION

The continuous provision of communications is essential for the operation of critical infrastructures, especially in military or emergency scenarios, where the loss of a communication link can disrupt information flow and coordination between network nodes. For this reason, modern communication systems incorporate redundancy mechanisms and link protection solutions to ensure service continuity even in the presence of disturbances [1].

In medium- and long-distance radio communications, radio relay systems are widely used due to their high capacity and rapid deployment. However, they rely on line-of-sight (LOS) conditions, which may not always be achievable. In such cases, tropospheric communications can be used as a backup solution, enabling long-distance transmission without direct visibility by exploiting wave scattering in the troposphere [2].

This paper analyses a hybrid communication architecture in which radio relay links serve as the primary transmission medium, while tropospheric links act as backup. Traffic switching between the two is performed automatically using the OSPF dynamic routing protocol, implemented in a virtualized environment. The radio links were modelled using the HTZ Warfare platform, and the routing infrastructure was deployed in EVE-NG, allowing the evaluation of network behaviour under both normal and failure conditions [3].

2. METHODS AND MATERIALS

2.1 HTZ Warfare Simulation Environment

HTZ Warfare is specialized software used for the planning and analysis of radio links in several types of operational scenarios, developed by the company ALTDI. The application allows the simulation of the propagation of electromagnetic waves, considering the technical parameters of the radio equipment, the characteristics of the terrain and the propagation conditions. With digital terrain models and geographic databases, the platform offers the possibility of calculating the radio link budget and evaluating its performance according to the parameters and characteristics of the equipment used, as well as the geographical environment, based on the propagation patterns of the radio channel [4].

2.2 Network Emulation Environment – EVE-NG

EVE-NG (Emulated Virtual Environment – Next Generation) is a network emulation platform used to simulate and test communication infrastructures in a virtual environment. The application allows the integration and interconnection of different types of

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virtual network equipment, providing the possibility of replicating complex topologies without the use of physical equipment. Through this platform, routing protocols, redundancy mechanisms and various operating scenarios of IP networks can be configured and tested, making it a useful tool for analysis, testing and research in the field of data communications [5].

2.3 Radio relay link modelling

The radio relay link was modelled in HTZ Warfare by defining the geographical position of the network nodes and configuring the technical parameters of the radio equipment used. During the simulation, the locations for the transmitting and receiving stations were selected, along with the main characteristics of the radio system, to reproduce the signal propagation conditions in the analysed geographical environment.

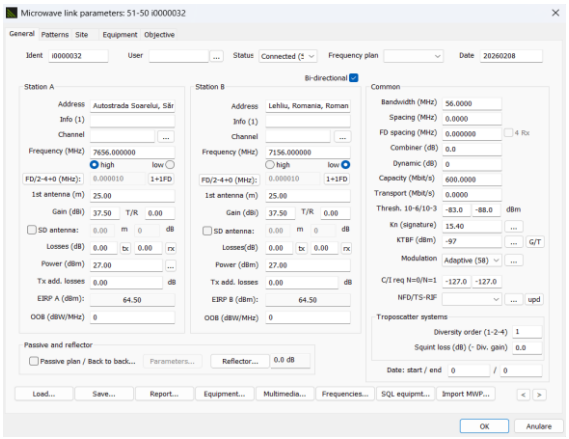
The topology of the radio relay link was created using digital terrain models and geographic databases available within the simulation platform, allowing the analysis of the radio path and the evaluation of propagation conditions between communication nodes. In the analyzed scenario, several locations in Romania were selected, including Bucharest, Buzău, Focșani, Bacău, Iași and Galați, which represent the main nodes of the network.



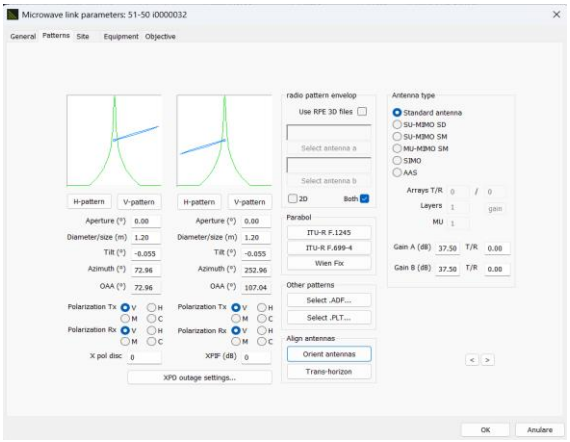
Figure 1 Topology of the radio relay network used in the simulation scenario

The main parameters of the radio relay system used in the simulation, such as operating frequency, transmitting power and radio system characteristics, were defined according to the specifications of the equipment used, namely the IP-20G. The operating frequency was automatically selected by the simulation platform in the range 7.1–8.5 GHz, corresponding to the band used for radio relay communications (Figure 2(a)).

During the simulation, the characteristics of the antenna used, type Am-4-7_8-CIRC-CR1, were also defined, which influenced the performance of the radio link and the calculation of the link budget. The antenna used is a directional antenna, with a diameter of 1.2 m, having the general characteristics specific to parabolic antennas used in radio relay systems (Figure 2(b)).



(a) Radio relay system parameters



(b) Characteristics of the antenna used

Figure 2 Parameters of the radio relay system and characteristics of the antenna used

2.4 Tropospheric link modelling

To increase the resilience of the communication system, a tropospheric link was added to the created scenario, used as a backup link in case of unavailability of the radio relay link. The topology of this link was created in HTZ Warfare by defining nodes between the cities of Bucharest, Focșani, Galați and Iași, these being considered strategic locations hosting important military units (Figure 3).

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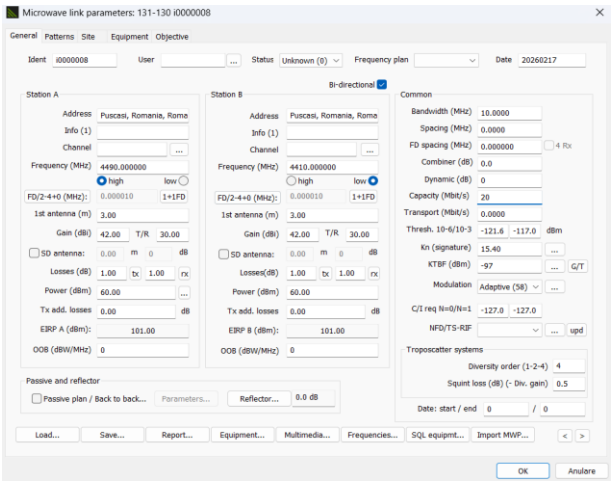
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Figure 3 Tropospheric network topology used in the simulation scenario

Tropospheric communications are based on the phenomenon of scattering of electromagnetic waves in the lower layer of the atmosphere (troposphere), which allows communications to be carried out over long distances even in the absence of direct visibility between stations. With this method, a small part of the energy of the transmitted signal is scattered in the troposphere and can be received by the remote station.

The main parameters of the tropospheric link used in the simulation were defined according to the characteristics of the equipment used, namely the tropospheric modem Datum M7 (Figure 4(a)). The operating frequency was automatically selected by the simulation platform in the 4.4–5 GHz range, specific to ground-level communication systems. The Tropoline 240 antenna was used to make the link, which is common in tropospheric communication systems due to its high gain and directive characteristics. The antenna used has general characteristics specific to this type of antenna, being used to ensure the performance of the tropospheric link (Figure 4(b)).



(a) Parameters of the tropospheric system



(b) Features of the Tropoline 240 antenna

Figure 4 Parameters of the tropospheric system and characteristics of the antenna used

2.5 Configuring the Routing Protocol and Failover Mechanism

To achieve the redundancy mechanism at the IP network level, the OSPF (Open Shortest Path First) dynamic routing protocol was used, configured in the EVE-NG emulation environment using MikroTik virtual routers. The routers were interconnected according to the network topology, allowing the exchange of routing information between the system nodes and the automatic determination of the optimal route for the transport of data traffic.

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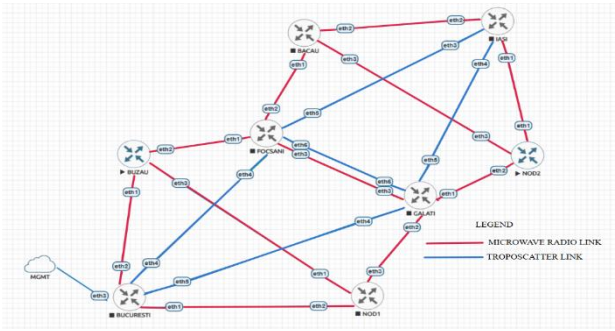


Figure 5 Hybrid Microwave–Troposcatter Network Topology

The configuration of the routers within the simulated network was carried out using the MikroTik RouterOS operating system. The complete configuration details for one of the routers are available online in a public repository at the following address, providing full access to the implemented parameters, routing mechanisms, and failover configurations used within the network: https://github.com/CiofirdelCristian/hybrid-radio-network-config.

The configuration includes the IP addressing setup and the initialization of the OSPF protocol, including the assignment of IP addresses to each interface, the configuration of a loopback address used as the router ID, and the inclusion of interfaces in the backbone area.

Additionally, the configuration defines the implementation of troposcatter links and the assignment of OSPF costs, where these links are configured with higher cost values to serve as backup routes, while microwave radio relay links are used as primary paths.

Furthermore, OSPF optimization and failover mechanisms are implemented through the adjustment of hello and dead intervals, as well as the use of the Netwatch tool for link monitoring. In the event of primary link degradation, the OSPF cost is dynamically modified, enabling traffic rerouting over backup links and controlled restoration to the primary path once the connection stabilizes.

3. RESULTS AND DISCUSSION

3.1 Results of the radio link simulation

In the simulation, the parameters of the radio relay links were configured so that their transmission capacity is between 400 and 600 Mbps. Under these conditions, the maximum distance between two stations is approximately 20 km, a value determined according to the propagation conditions, the characteristics of the radio equipment used and the performance requirements of the system. To ensure reliable and stable operation in the simulation, a minimum link availability of 99.95% was imposed and the fading margin was set to approximately 20 dB.

The profile of a radio relay link obtained from the simulation is shown in Figure 6. The analysis of the terrain profile allows the evaluation of the propagation conditions between the two communication stations and the verification of the existence of direct visibility (LOS – Line of Sight) between them. From the analysis of the profile, the line of sight between the nodes is maintained over the entire distance of the connection, and the First Fresnel zone is not significantly obstructed by relief.

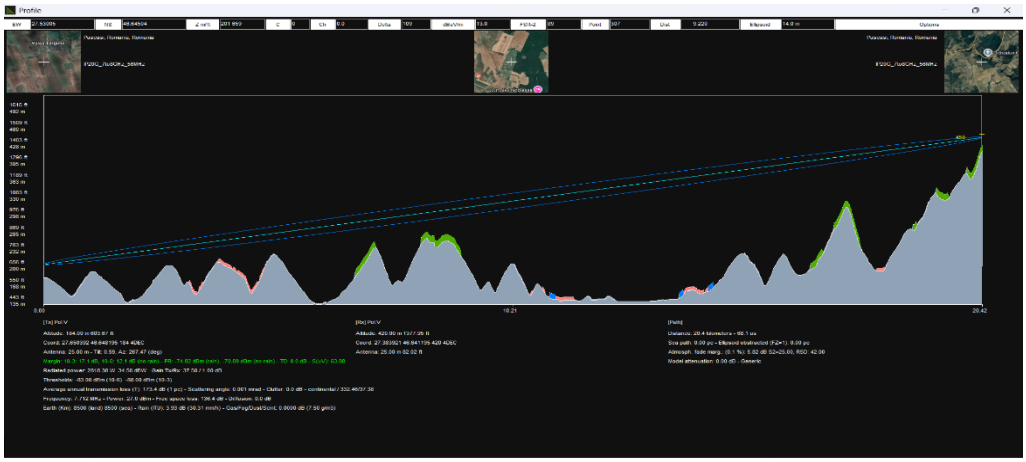


Figure 6 Profile of the radio relay link and analysis of visibility conditions

During the simulation, situations were also identified in which the first Fresnel zone is partially obstructed by relief (Figure 7). However, the degree of obstruction does not exceed 60% of the Fresnel zone, a value that allows the link to be maintained without significant degradation in performance. Therefore, the radio relay link can be considered feasible and reliable under the existing conditions.

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Figure 7 Example of a radio relay link profile in which the first Fresnel zone is partially obstructed by relief.

3.2 Results of the tropospheric link simulation

To evaluate the performance of the tropospheric link, the main parameters of the communication system were analysed. The simulation aimed to determine a reliable communication distance, as well as the link performance under configured system conditions. Also, for the evaluation of the reliability of the system, a minimum availability of 99.95% was imposed. Under these conditions, the transmission capacity was configured in the range of 5–25 Mbps, varying depending on the propagation conditions.

An example of the tropospheric link profile obtained in the simulation is shown in Figure 8. The analysis of the results indicates that the distance between the two tropospheric stations is approximately 144 km, significantly greater than in the case of radio relay links. Under the conditions of the parameters configured in the simulation, the link has a fading margin of approximately 18 dB, which allows the stable operation of the system to be maintained. For these operating conditions, the estimated transmission capacity of the link is approximately 20 Mbps, which is sufficient to ensure the operation of the backup link within the proposed communication architecture.



Figure 8 Tropospheric Link Profile and Propagation Analysis

3.3 Network behaviour and failover mechanism

To evaluate the behaviour of the network in normal operation scenarios and in failure situations, it was analysed how the OSPF routing protocol handles the routes available in the network. Under normal operating conditions, the traffic between the nodes of the network is routed through the radio relay links, which are configured with a lower OSPF cost.

To verify the redundancy mechanism implemented in the network, the traceroute command from the router located in the Bucharest node to the destination address in Iași was used. Under normal operating conditions, traffic is directed through radio relay links, the route of the packets being Bucharest – Nod1 – Galați – Nod2 – Iași. After deactivating the interfaces corresponding to the radio relay links in Bucharest, the OSPF protocol automatically recalculated the routing table, and the traffic was redirected through the tropospheric link to the Galați node, after which it continues through the existing radio relay infrastructure to the destination. In this situation, the route becomes Bucharest – Galați – Nod2 – Iași. This change of route confirms the correct operation of the failover mechanism and the ability of the network

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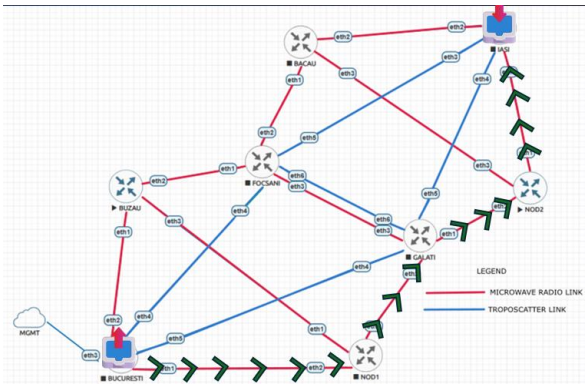
to maintain continuity of communications in the event of the unavailability of the main link (Figure 9).

```
[admin@BUCURESTI] > /tool traceroute 10.255.0.5
ADDRESS                          LOSS SENT    LAST     AVG    BEST   WORST STD-DEV STATUS
10.0.0.6                           0%   61     1ms     1.7     0.7    19.8     2.4
10.0.0.41                          0%   61   1.9ms     2.9     1.3    36.6     4.4
10.0.0.37                          0%   61   2.9ms     6.4     2.2   180.2    22.5
10.255.0.5                         0%   61   4.3ms     6.5     3.2   125.3    15.4

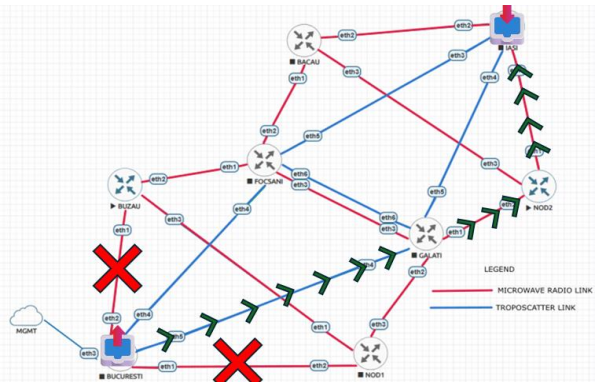
[admin@BUCURESTI] > /interface disable ether1
[admin@BUCURESTI] > /interface disable ether2
[admin@BUCURESTI] >
[admin@BUCURESTI] > /tool traceroute 10.255.0.5
ADDRESS                          LOSS SENT    LAST     AVG    BEST   WORST STD-DEV STATUS
10.0.100.6                         1%   97   1.1ms     1.7     0.8     4.2     0.5
10.0.0.37                          0%   97   2.1ms     2.8     1.6     5.5     0.7
10.255.0.5                         0%   97   3.3ms     3.3     1.7     8.3     0.8
```

Figure 9 The route of network traffic under normal conditions and after the failover mechanism is activated.

The visual representation in Figure 10 supports the previously described behaviour of the routing process. Under normal operating conditions, the traceroute output confirms that traffic is transmitted through the primary radio relay links. After the intentional deactivation of these links, the routing path is automatically modified by the OSPF protocol, redirecting the traffic through the troposcatter link [6-9]. This visual evidence clearly illustrates the dynamic rerouting capability of the network and validates the correct operation of the implemented failover mechanism.



(a) Traffic routing under normal conditions through the primary radio relay links.



(b) Traffic rerouting after failover, using the troposcatter link as a backup path.

Figure 10 Visual representation of network traffic routing under normal operating conditions and after the activation of the failover mechanism.

4. CONCLUSIONS

The paper presented the creation and analysis of a hybrid communications architecture in the microwave range, using radio relay links as the main infrastructure and tropospheric links as a backup solution. The modelling and evaluation of the performance of the radio links were carried out using the HTZ Warfare simulation platform, and the behaviour of the IP network was analysed in an EVE-NG emulation environment.

The results of the simulations showed that radio relay links for capacities of 400-600 Mbps can provide transmission over distances of about 20 km between stations, while tropospheric links allow communications over significantly longer distances of more than 100 km, but with a lower transmission capacity, located in the range of 5–25 Mbps. These characteristics make tropospheric links suitable for use as a backup solution in critical communication networks.

The integration of the two types of links in a network infrastructure based on the OSPF routing protocol allows the implementation of an automatic failover mechanism, whereby traffic is redirected to the tropospheric link in case of unavailability of the main radio link. The results obtained show how this approach works and highlight the potential of using a hybrid architecture to increase the resilience of communication systems.

5. CREdit authors statement

Conceptualization: C.C., S.A.; Data curation: C.C.; Formal analysis: C.C.; Funding acquisition: not applicable; Investigation: C.C.; Methodology: C.C., S.A.; Project administration: S.A.; Resources: C.C.; Software: C.C.; Supervision: S.A.; Validation: C.C., S.A.; Visualization: C.C.; Writing – original draft: C.C.; Writing – review & editing: C.C., S.A..

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THE ECONOMIC IMPACT OF DIGITALIZATION IN MARITIME LOGISTICS

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Abstract: The maritime transport sector is undergoing profound transformations driven by digitalization, transitioning modern ports from simple freight transit points into smart logistics hubs. This paper aims to analyse the extent to which digital technologies—specifically Artificial Intelligence (AI), Blockchain, and the Internet of Things (IoT)—have contributed to the economic performance of the Port of Constanța. Based on statistical data from the 2020-2025 period, the research methodology evaluates traffic variations, capacity efficiency, and applies economic formulas to determine the Compound Annual Growth Rate (CAGR) and estimated cost savings. The results reveal that the existing digital infrastructure enabled the port to successfully absorb severe geopolitical shocks and immense volume fluctuations, achieving a structural growth CAGR of 2.28% per year and generating estimated operational savings of 443.9 million euros over the analysed timeframe. In conclusion, digitalization fundamentally restructures maritime logistics and generates quantifiable economic benefits. To maintain competitiveness and align with strict European regulatory frameworks, the Port of Constanța must urgently accelerate investments in cybersecurity, integrated digital ecosystems, and skilled workforce training to fully capitalize on its potential as a leading European digital hub.

Key words: Artificial Intelligence, Blockchain, Digitalization, Economic impact, Maritime logistics, Port of Constanța.

1. INTRODUCTION

In the context of the rapid transformations brought about by digitalisation, the maritime transport sector is going through a period of profound change, with significant economic implications at global, European and national level. Modern ports have gone from freight transit points into smart logistics hubs, where digital technologies are redefining operational efficiency and cost structure.

The Port of Constanța is the largest port with access to the Black Sea and one of the most important ports of the European Union, and represents a relevant and current case study for the analysis of these transformations. It has had a spectacular evolution in recent years, with a significant increase from 75.5 million tons in 2022 to the historical record of 92.6 million tons in 2023 [38], [57]. The drop to 67.5 million tons in 2025 shows both the huge potential of digitalization and the vulnerabilities of a system still in transition.

This paper aims to analyse, based on statistical data from the period 2020-2025, the extent to which digitalization has contributed to the economic performance in the Port of Constanța, while presenting the challenges and opportunities for the next period. The digital technologies analysed will be: artificial intelligence, blockchain and IoT systems.

2. DIGITAL TECHNOLOGIES IN MARITIME LOGISTICS

2.1 Artificial Intelligence (AI)

Artificial intelligence is a technology that has transformed the maritime sector in recent years, developing it very rapidly. A report by Lloyd's Register [5] states that the maritime AI market has grown rapidly, reaching a value of $4.13 billion in 2024, Growing almost three times compared to the previous year, with an annual growth rate of 23% projected for the next five years. This rapid development shows the concrete usefulness of AI in solving certain operational problems of the maritime sector. More than 70% of shipping companies will integrate AI technologies by 2025, to drive efficiency and innovation and to navigate the challenges of a dynamic global market.

Optimizing shipping routes is the most practical application of AI in shipping. With the help of AI route optimization systems, fuel consumption can be reduced by up to 10-15% [6], [7]. These systems are based in particular on choosing more energy-efficient routes,

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minimising downtime and avoiding adverse weather conditions. In January 2025, HD Hyundai Marine Solution launched OceanWise, a carbon emission management and navigation optimization platform through big data algorithms to significantly reduce fuel consumption and greenhouse gas emissions. This system monitors emissions, optimizes routes according to the weather and uses digital twin technology to simulate the behaviour of the real ship in different conditions; it has also saved an average of 5.3% of fuel.

Predictive maintenance is another AI-powered system in the maritime sector. Companies such as Rolls-Royce and Wärtsilä have developed autonomous systems capable of short uncrewed voyages, based on sensors, LIDAR, radar and satellite data that create a virtual environment for autonomous navigation [8], [27]. According to UNCTAD [2], more than 80% of global trade is carried out at sea; increasing pressures to optimize operations, reduce costs and minimize environmental impact make AI an indispensable technology for maritime authorities and regulators.

2.2 Blockchain

Blockchain is a technology that addresses excessive documentary bureaucracy and lack of transparency in the supply chain. Traditional transport processes involve multiple parties and large quantities of paper documents, leading to slow transfers of information and coordination difficulties. Blockchain offers a structural solution to this problem by creating a decentralized, immutable digital ledger that is accessible to all parties involved. The cost of a blockchain-based electronic bill of lading (eBL) is on average $15, which is about 15% of the price of a traditional bill of lading delivered by international courier [9], [11].

The impact of blockchain on the operational efficiency of ports has been demonstrated through rigorous academic studies [10]. These studies showed that blockchain technology reduces the average storage time of containers in the terminal by 3-4% and decreases the maximum storage time in the port yard by up to 30%, thus increasing the utilization rate of the equipment.

2.3 Internet of Things (IoT)

IoT transforms ports and ships from relatively opaque entities into fully transparent and real-time monitored systems. IoT applications in maritime logistics are diverse and have a direct impact on costs and safety. The smart container market is on a rapid growth trajectory, projected to reach USD 13.69 billion by 2030, with a compound annual growth rate of 19.6% from 2024 to 2030, driven by the growing demand for real-time visibility, enhanced commodity security, and data-driven decision-making in global supply chains [15], [16].

According to Gartner [12], IoT-based predictive maintenance reduces unplanned downtime by up to 30%, eliminates unnecessary repairs, generating savings of 15-25% in maintenance budgets [13]. IoT sensors installed throughout the port collect large volumes of data in real time, tracking container movements, monitoring equipment status, measuring environmental conditions, and detecting vessel positions [14], [17].

3. EUROPEAN AND NATIONAL REGULATORY FRAMEWORK

The European Union has adopted in recent years an ambitious legislative framework that requires the mandatory digitalisation of the maritime transport sector, with direct implications for all Member States. The EMSWe Regulation (EU) 2019/1239 [19], [20], applicable since August 2025, creates a decentralised network of National Maritime Single Windows that function as a single point of entry for the exchange of information in each Member State [21]. The economic impact is direct: operators operating in several European ports benefit from significant reductions in administrative costs. The eFTI Regulation (EU) 2020/1056, fully applicable from July 2027, aims to completely eliminate paper documents from all European modes of transport, with estimated savings of €27 billion for operators [22]–[25]. The inclusion of maritime transport in the EU ETS from 2024 adds additional financial pressure, mandating a 40% reduction in emissions by 2030 and forcing ports to invest in green technologies and digital emission monitoring systems.

At the national level, Romania has implemented the RO e-transport system, mandatory for international transports from July 2024, with penalties between 20,000 and 100,000 lei for non-compliance [28]–[30]. The Ministry of Transport has developed the Institutional Strategic Plan 2025-2028, which explicitly recognizes the gap with European standards and prioritizes the digitization of infrastructure [31]. Through the Transport Program 2021-2027, Romania has access to significant European funds for the modernization and digitization of ports, an opportunity insufficiently capitalized so far due to limited administrative capacity [32], [47].

4. CASE STUDY: PORT OF CONSTANȚA

The Port of Constanța is the most important logistics hub of Romania and one of the most significant ports of the European Union. The Port of Constanța can process up to 120 million tons of cargo annually, being equipped with modern facilities, including specialized terminals for containers, grain, oil and other general cargo. It also has passenger and cruise ship terminals. From a European perspective, the port occupies a remarkable strategic position. The Port of Constanța recorded in 2022 the third highest percentage increase in freight traffic among the ports of the European Union [36], [39].

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Table 1 Constanța Port Traffic 2020-2025 (Source: authors' study)

Year	Total Traffic (mln tons)	Absolute variation (mln tons)	Percentage variation (%)	Main Context
2020	60.3	-6.3	-9.5%	COVID-19 pandemic
2021	67.4	+7.1	+11.8%	Post-pandemic recovery
2022	75.5	+8.1	+12.0%	Ukraine War
2023	92.6	+17.1	+22.6%	Historical peak
2024	77.5	-15.1	-16.3%	Resumption of Ukrainian ports
2025	67.5	-10.0	-12.9%	Traffic normalization

Annual Growth Rate (%)

$$Growth\ rate = \frac{Traffic\ year\ N - Traffic\ year\ N-1}{Traffic\ year\ N-1} \times 100 \quad (1)$$

Application: 2019-2020: -9.5% ; 2020-2021: +11.8% ; 2021-2022: +12.0% ; 2022-2023: +22.6% ; 2023-2024: -16.3% ; 2024-2025: -12.9%

Compound Annual Growth Rate (CAGR)

$$CAGR = \left(\frac{Final\ Value^{\frac{1}{N}}}{Initial\ Value} - 1\right) \times 100 \quad (2)$$

$$\text{CAGR} = \left(\frac{67{,}5^{\frac{1}{5}}}{60{,}3} - 1\right) \times 100 \Rightarrow \text{CAGR} = +2.28\%/\text{year} \quad (3)$$

Port Capacity Efficiency Index

$$\text{Capacity efficiency} = \left(\frac{\text{Real Traffic}}{\text{Maximum capacity}}\right) \times 100 \quad (4)$$

Absolute Variation from Baseline

$$\text{Absolute variation from baseline} = \left(\frac{\text{Traffic year N} - \text{Traffic 2020}}{\text{Traffic 2020}}\right) \times 100 \quad (5)$$

Estimated Economic Impact of Efficiency Gains

$$\text{Digitalization savings} = \frac{\text{Operational cost}}{\text{Ton}} \times \text{Total traffic} \times \text{Discount rate} \quad (6)$$

Table 2 Estimated Economic Impact (Source: authors' study)

Year	Traffic (mln tons)	Est. total cost (mln. EURO)	Savings 25% (mln. EURO)	Capacity Efficiency	Absolute change
2020	60.3	192.0	48.0	50.3%	0%
2021	67.4	236.3	59.1	56.2%	+11.8%
2022	75.5	302.4	75.6	62.9%	+25.2%
2023	92.6	388.5	97.1	77.2%	+53.6%
2024	77.5	345.8	86.5	64.6%	+28.5%
2025	67.5	310.5	77.6	56.3%	+11.9%

The analysis of data from the period 2020-2025 allows the identification of three distinct phases in the evolution of the Port of Constanța:

Phase 1 – Recovery (2020-2021): The port recovered from the pandemic impact, recording an increase of +11.8% in 2021. The digitization of document operations and the early adoption of digital traffic management systems have contributed to operational flexibility.

Phase 2 – Geopolitical tensions and accelerated digitalization (2022-2023): The context of the war in Ukraine has generated exceptional growth, with the port reaching 92.6 million tons in 2023. This period demonstrated that the existing digital infrastructure could absorb dramatic increases in volume without major bottlenecks.

Phase 3 – Normalization and restructuring (2024-2025): The return of Ukrainian traffic to its own ports has reduced volumes, but the port's traffic in 2025 was 11.9% higher than in 2020, confirming a real structural growth. The operating revenues of the port administration company fell by 8.6% in 2024, and for 2025 the budget provides for a further decrease of 491.6 million lei.

The Port of Constanța significantly accelerated investments in the analysed period. Investments worth over 756 million euros are underway and in preparation in the Port of Constanța, including the modernization of the electricity distribution infrastructure, the extension of the quays and the electrical connection of the ships to the quay (Cold Ironing system) [42].

A large-scale project for the Port of Constanța is the development of Piers III S – IV S, with an estimated value of over 1 billion euros. Also, the development of the artificial island is estimated at over 1.4 billion euros. The total planned investments thus exceed 3.2 billion euros, representing the largest modernization in the history of the port [41].

5. CHALLENGES AND RISKS OF DIGITALIZATION

5.1 High implementation costs

One of the most significant barriers to maritime digitalisation is the substantial upfront investment needed to modernise existing systems. Installing digital systems on board ships costs between $0.5 million and $2 million per ship, and upgrading port terminals involves hundreds of millions of euros. Interviewing

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global industry leaders reveals common challenges: incompatible legacy systems, data sharing concerns, and IT skills gaps [48]. Resistance to change often stems from high implementation costs and managerial fear of reducing workload requirements. Trade unions frequently view digitalization with scepticism, believing that it would lead to a decrease in the demand for personnel. These challenges are particularly relevant for the Port of Constanța, which operates with infrastructure built largely during the communist period and which requires major investments to bring it up to European standards.

5.2 Skills gap and labour force

The digital transformation creates an acute demand for qualified personnel in niche technical fields, generating a significant gap with the existing supply on the labour market. The transition to digitized operations requires a proficient workforce in advanced technologies, and the labour gap in the industry is shifting from quantity to quality. At the level of the Port of Constanța, this challenge is amplified by the national context: Romania is facing a massive phenomenon of emigration of qualified labour.

5.3 Cyber vulnerabilities

Cyber risk is the most dynamic and dangerous type of risk associated with maritime digitalisation. The number of maritime cyber incidents in 2025 increased by 103% compared to 2024, with DDoS, ransomware and malware attacks accounting for the majority of them [50], [52]. An analysis based on 112 incidents from 2020-2025 reveals a 150% increase in incidents, with state-sponsored actors from Russia, China, and Iran responsible for the most high-impact attacks [51], [53], [56].

5.4 Geopolitical and external factors

The Port of Constanța has proven to be extremely vulnerable to external geopolitical factors, as illustrated by the dramatic evolution of traffic in the period 2022-2025. Global maritime trade grew modestly by 2.2% in 2024 and is projected to stagnate at just 0.5% in 2025 [54]. Traffic through the Suez Canal has fallen by 70% from the peak level, forcing ships to be rerouted on longer and more expensive routes [55]. At the local level, the resumption of activity of Ukrainian ports reduced Constanța's traffic by 25.1 million tons between 2023 and 2025, a decrease of about 27% in two years. This dependence on external factors underlines the structural vulnerability of the port and the need to diversify cargo types and trade routes through digital tools.

6. CONCLUSIONS AND RECOMMENDATIONS

The analysis of real-world data from 2020-2025 confirms that digitalisation generates quantifiable economic benefits and structurally transforms maritime logistics. The application of economic formulas on the data of the Port of Constanța demonstrated estimated savings of 443.9 million euros over the entire analysed period, a structural growth CAGR of 2.28%/year and a remarkable capacity to absorb external shocks.

The European legislative framework (EMSWe, eFTI, EU ETS, TEN-T) imposes a strict digitalisation timetable that creates financial pressures, but also ensures access to European funding and alignment with the competitive standards of Western European ports. Romania has taken concrete steps through the RO e-Transport system and the MTI Strategic Plan 2025-2028, but the pace of implementation remains insufficient compared to the needs.

- Accelerating the absorption of European funds from the 2021-2027 Transport Program and PNRR for port digitalization projects
- Urgent implementation of a cybersecurity plan aligned with the CER Directive (EU) 2022/2557 and the IACS UR E26/E27 standards
- Investing in skilled workforce training and closing the skills gap in critical areas
- Building an integrated digital ecosystem that connects all port components: terminal, customs clearance, rail logistics, electronic documentation
- Diversifying the types of goods processed to reduce dependence on Ukrainian traffic
- Partnerships with European reference ports for the transfer of best practices and the acceleration of digitalization.

The Port of Constanța is at a strategic crossroads. The announced investments of 3.2 billion euros, the European legislative framework and the privileged geographical position at the confluence of trade routes between Europe, Asia and the Middle East offer all the premises for transformation into a leading European digital logistics hub. The realization of this potential depends on a single determining factor: the speed and quality of the implementation of digitalization in all the parameters analysed in this paper.

7. CREdit authors statement

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PREFERENCES OF *HIPPOCAMPUS GUTTULATUS* INDIVIDUALS FROM THE BLACK SEA FOR IRON AND STAINLESS STEEL ARTIFICIAL REEFS

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Abstract: The implementation of artificial habitats made from recycled materials can significantly enhance marine habitats for seahorses and other species, especially in areas where the natural habitat has been altered by anthropogenic factors such as pollution, trawling, beach enlargement, eutrophication, invasive species, and climate change. The "Seahorse House" (Romanian: "*Casa căluților de mare*") is a small project conducted by Club Marine Explorer NGO in partnership with academic institutions that aims to help conserve *Hippocampus guttulatus* (Cuvier, 1829) individuals on the Romanian shore through the "seahorse hotel" model of artificial reefs. The seahorse hotel replicas were made with the target individuals' behaviour in mind; they cling to natural or man-made structures with their prehensile tails. The project established four key distinct locations for these reefs along the coast of Constanța city on different substrate types: sand, rocky, and mixed. Two distinct types of artificial habitats were placed at each installation sector, which were made from recycled iron, stainless steel, and rope. In addition, the nutrient levels for each placement zone were analysed using the rapid kits Viscolor HE and Viscolor ECO for phosphate and nitrate ions, respectively; in addition, the pH was monitored with the help of Merck MQuant™ Universal pH Indicator Solution. Moreover, the presence of total coliform and faecal coliform bacteria was assessed using CompactDry™ TC and CF culture dishes. Overall, the placement areas were in no peril of eutrophication or any bacterial infestation from the point of view of the rapid kits and the dry culture dishes, except for one of the zones, which is the closest to the piers and the touristic port. Ultimately, the iron reefs were more successful than their stainless-steel counterparts. Thus, it has been concluded that marine life may be attracted to underwater iron structures.

Keywords: artificial reefs, ions, iron, nutrients, seahorses, stainless steel.

1. INTRODUCTION

The Black Sea is considered a "Unicum Hydrobiologicum", as the marine oceanographer Nikolay M.Knipovich put it, meaning its ecosystem is one of a kind; therefore, it needs to be protected from anthropogenic harmful influences.

The research was conducted within the "Seahorse House" project, which provides students from Constanța County the chance to explore and protect the marine environment of the Black Sea through educational and scientific activities. Participants designed, built and installed artificial reefs by the shore of the Romanian coast, creating safe habitats for seahorses (Hippocampus gutulatus) and other marine species. Carried out between May and November 2025, the project is implemented by Club Marine Explorer NGO, in partnership with high school and university students, covering a large part of the public regarding species conservation.

2. METHODOLOGY

The artificial reefs of the project followed the „seahorse hotel" model [l] to help seahorses attach to them with their prehensile tail. Seahorses live at a short distance from the shore, on sandy and rocky bottoms and usually cling with their prehensile tail to marine plants and other anthropogenic structures [2]. The placement of the reefs was followed by water sampling and analysis to determine the nutrient levels and the possibility of a eutrophication threat.

The reefs are in four distinct locations; the coordinates and other specifications are given in Table 1 and Figure 1 (the areas were numbered in the order of the reefs' placement from Z1 to Z4 and were located on

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the map using Google Earth). The first location area (Z1) is near the pier at the Malibu Hotel beach, located at the deepest of the four areas, 8.3 meters below sea level, on a sandy substrate; Z2 is inside the pier in the area of the former fisher zone, located at the shallowest point of all, 3 meters, on a rocky substrate; Z3 is located the furthest offshore, perpendicular to the Malibu Hotel, at a depth of approximately 8 meters on a combined sandy and rocky substrate; and the last location area, Z4, is located right at the mouth of the tourist port, at a short distance from the breakwater, with a depth of around 4 meters, on a mostly rocky substrate. The reefs were monitored in 2025 in August-September, but the Z1 reef could no longer be found at the end of September.

The water samples were collected in plastic containers, which were individually labelled immediately after sampling. For each sample, essential details about the sampling site were recorded to ensure monitoring and facilitate subsequent inventories within the Engineering and Environmental Protection Laboratory of the Maritime University of Constanta. The wind speed did not exceed level 2 on the Beaufort scale during monitoring.

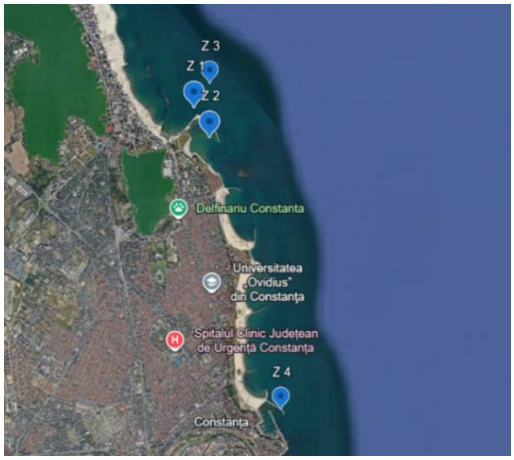


Figure 1. Placement areas of the reefs

Table 1. Specifications for artificial reefs location

Location number	Coordinates		Depth (m)	Substrate
	Latitude	Longitude		
1	44°13’19” N	28°38’46” E	8.3	Sandy
2	44°13’03” N	28°39’02” E	3	Rocky
3	44°13.3’32” N	28°38’58” E	8	Sandy and Rocky
4	44°10’39” N	28°39’51” E	4	Rocky

To determine the pH value, Merck MQuant™ Universal pH Indicator Solution was used. To a 5mL sample of water, 5 drops of indicator solution were added, then the sample was analysed calorimetrically. Chemical analyses to determine the level of eutrophication were performed by the colorimetric method, using the rapid Viscolor HE and Viscolor ECO kits for phosphate and nitrite ions, respectively. The method involves staining the samples through chemical reactions using 6 drops of 15-30% sulfuric acid and 10-25% sodium disulphate for phosphate ions, and for nitrite, 4 drops of $(NO_2)^{-1}$ and a measuring spoon of $(NO_2)^{-2}$ were added. After adding the reagents, both samples were left for 10 minutes to react. After the staining time, the samples were analysed calorimetrically using coloured cards, blue for phosphates and yellow-pink for nitrite.

For the bacteriological determination, we used CompactDry™ TC (total aerobic microorganisms) and CF (coliform bacteria) culture plates. The cultures were incubated for 24 hours at 37°C, after which the colony spots on the Petri dishes were counted. Once the colonies had been counted, the following formulas were used to determine their density:

$$\frac{\text{CFU}}{\text{mL}} = \frac{\text{number of CFUs}}{\text{sample volume} * \text{dilution factor}} \quad (1)$$

$$\frac{\text{CFU}}{\text{cm}^2} = \frac{\frac{\text{CFU}}{\text{mL}}}{\text{plate surface area}} \quad (2)$$

The reefs were built by high school students with the guidance of staff from the NGO Club Marine Explorer. The iron reef has a three-dimensional size of 50x50x50 cm, with a horizontal bar for stability connecting the edges on each side face approximately 17 cm from the base. One face of the cage has only the stability bar, while two of them also have two stainless steel wire cables parallel to the substrate, arranged at almost equal distances from each other. The third plane of the artificial habitat has three vertical and four horizontal stainless-steel wires, and the top of it has an iron rod in the middle, along with a matrix of eight stainless alloy wires connected horizontally and vertically to the edges of the cube (Figure 2 and Figure 4). The stainless steel one has a size of 70x70x70 cm,

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with fabric ropes on the faces of the cage, connected to its edges (Figure 3 and Figure 4).



Figure 2. The iron reef



Figure 3. The stainless-steel reef

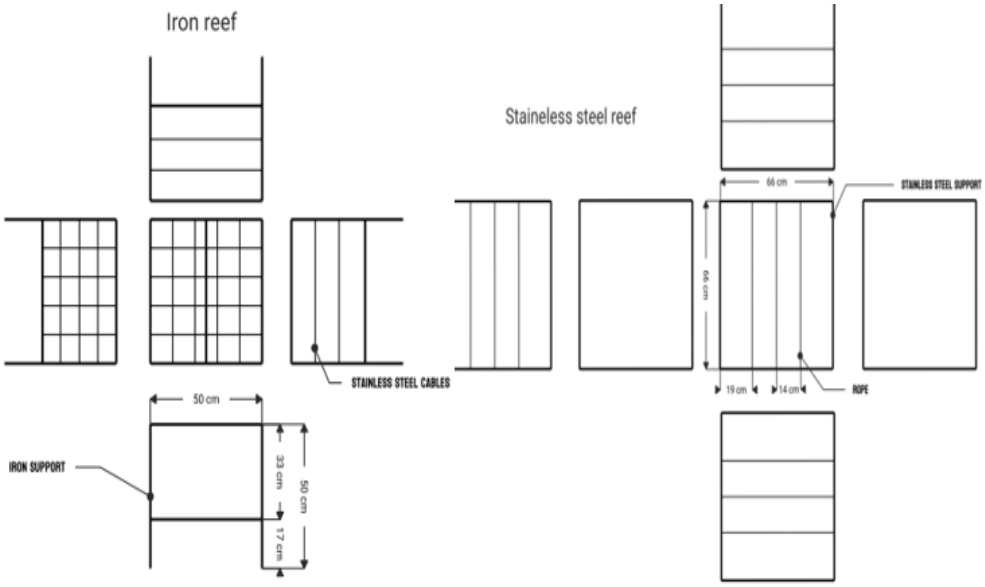


Figure 4. The iron reef (left) and the stainless steel (right) diagrams

3. DISCUSSIONS

Following the monitoring, from the point of view of analysing the nutrient level, it can be said that the reef locations are clean areas. The average concentration of nitrite ions is 0.04 mg/L NO_2^-, with the first three zones having a value of 0.02 mg/L NO_2^-, and Z4 recording 0.1 mg/L NO_2^-. The average of phosphate ions is higher than that of nitrite ions by 0.2 mg/L P. Surprisingly, Z3 contains the highest concentration, of 0.8 mg/L P, followed by Z4 with 0.1 mg/L P, while Z1 and Z2 have a concentration similar to that of nitrite ions, of 0.2mg/L P / mg/L NO_2^- (Figure 5). In addition, the waters of the Dobrogea region have an alkaline character; as a result, all the analysed samples registered 8.5 pH units with slight, insignificant variations.

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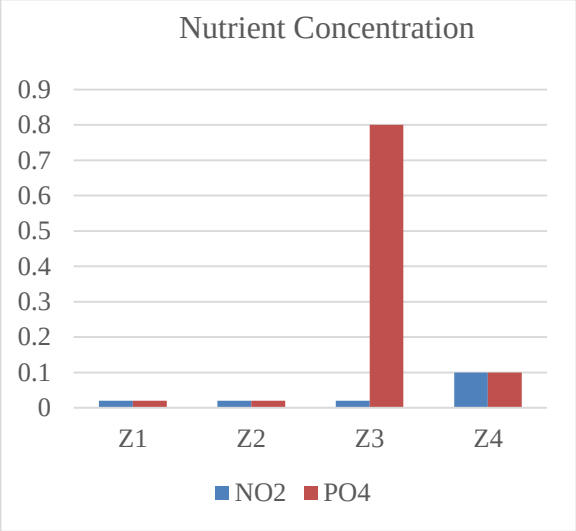


Figure 5. The nutrient concentration of each zone

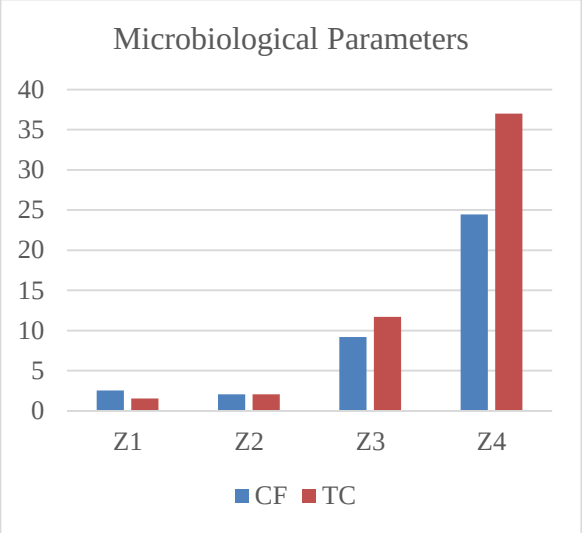


Figure 6. CF and TC parameters

CompactDry™ TC and CF cultures were used to determine the presence of coliform bacteria, which thrive in fresh or low-salinity waters—such as the Black Sea, where salinity reaches a maximum of 18 PSU during periods of drought. These bacteria can also be introduced by rivers, such as the Danube, and transported to the coastal zone by the sea's circular currents. Z4 was the only site with high levels of CF (24.45 CFU) and TC (37 CFU). This value can be linked to the specific area where the reef was installed: located at the entrance to the Tomis tourist harbour, the site receives wastewater discharged directly from boats, and the presence of bathers in the area may also contribute to the introduction of these bacteria. Z3 follows, with the next highest levels of CF and TC, 9.17 CFU and 11.7 CFU, respectively. This area is located offshore, where the sea's circular currents may transport these types of bacteria from the mouth of the Danube Delta toward the coastline. Z2 and Z1 show normal levels of FC and TC: 2.04 CFU and 2.04 CFU for Z2, and 2.55 CFU and 1.53 CFU for Z1 (Figure 6).

The iron habitats undergo an electrochemical corrosion process that produces rust. The rusting process occurs in two stages:

Stage I consists of the iron oxidation (in which atoms give up two electrons and form ferrous ions) and the electrolyte reduction (the corrosive agents that affect reefs are seawater and oxygen dissolved in water), according to the following formulas and scheme:

Iron oxidation:

$$Fe^{0} \rightarrow Fe^{+2} + 2e^{-} \quad (3)$$

Electrolyte reduction:

$$H_2O + \frac{1}{2} O_2 + 2e^{-} \rightarrow 2(OH)^{-} \quad (4)$$

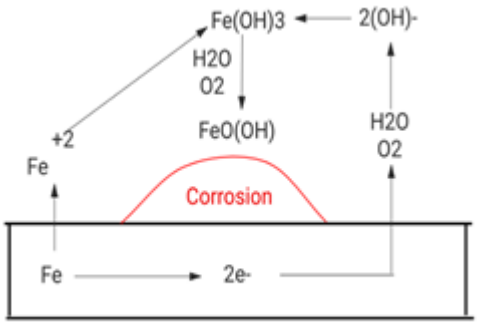


Figure 7. Diagram of rust formation on iron surfaces

In the second stage, the removed ferrous ions are oxidised in turn and form ferric ions ($Fe^{+2} \rightarrow Fe^{+3}$). The ferrous and ferric cations removed by the metal rods fall into the category of trace elements (elements that are part of the composition of living organisms) and attract marine animals to the reefs.

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The other type of reefs has not been of great interest to any marine species, as stainless steel is an inert alloy, made of iron in combination with other semi-noble elements (nickel, chromium, aluminium, etc.) that stop oxidation. The redox reaction does not occur because non-oxidising metals form a thin passivating layer of metal oxide on the surface of the material that stops oxygen molecules from interacting with the other compounds in the structure.

Habitat Z3 was the most successful of the four areas, with a population of seven seahorses attached to the iron reef (Figure 7), while the stainless reef was not populated by any individuals. Moreover, not only are seahorses present at the reef, but it is also populated by other syngnathids, clams and benthic fish. The preference of individuals of the target species towards the iron reef solidifies the idea of a trace element attracting marine animals.



Figure 8. The Z3 iron habitat

4. CONCLUSIONS

The zones in which the reefs are localised are conventionally clean, free of eutrophication threats, except for the third area, where phosphate concentration was highest, and the fourth one where a high quantity of bacteria has been registered. As for the reef's yield, iron reefs showed a greater preference between the two types, not only for the targeted species, but for other marine animals in general. This is further strengthened by the release of trace elements such as ferrous ions and the presence of various species at the reef.

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FROM THE LECTURE HALL TO THE DECK: PSYCHOLOGICAL CHALLENGES OF FEMALE CADETS ON THEIR FIRST VOYAGE

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Abstract: Maritime universities today proudly showcase a growing number of female students training to become officers. However, the real test does not happen in the simulator room. It hits during that very first voyage. Moving from a familiar university campus to a commercial vessel in the middle of the ocean is a massive culture shock. Academies do a great job teaching ship stability and navigation, but female cadets often step on board feeling unprepared for the emotional toll. They face unique and often unspoken pressures like deep social isolation, the stress of adapting to life at sea, and the heavy burden of constantly proving themselves in a male-dominated environment. This paper argues that technical know-how is no longer enough to guarantee a successful start. To truly support these young women, maritime education needs to address the human element.

Key words: Female cadets, Maritime education, Psychological resilience, Soft skills, First voyage adaptation.

1. INTRODUCTION

Walking through the corridors of a maritime university today looks very different than it did a couple of decades ago. You see young women heading to classes with backpacks and course notes just like any other college students, but with their sights set on building careers on giant container ships, tankers, or luxury cruises. International bodies like the IMO push hard for gender equality, and universities are genuinely proud of their diverse enrollments. But getting a civilian diploma and passing simulator exams is only half the battle.

The real test begins the moment a student steps onto the deck of a commercial ship for their very first voyage as a cadet. Imagine being twenty years old, thousands of miles from home, and stepping into a closed metal environment where you might be the only woman among a crew of twenty or thirty men. The safety bubble bursts immediately.

Suddenly, knowing how to flawlessly calculate the stability of a cargo vessel does not help you figure out how to deal with a traditional chief mate who doubts your abilities simply because of your gender.

This paper will take a closer look at that exact transition. We will explore the psychological shock of the first voyage. Female cadets face a unique set of challenges that go far beyond ordinary homesickness. We will analyse the reality of deep social isolation and the unspoken pressure of representation. Often, a female cadet feels that if she makes a simple mistake, she is not just a junior making a learning error. She feels like she is proving a harmful stereotype right.

Maritime universities are fantastic at producing highly skilled civilian navigators and engineers. But there is a glaring blind spot. We spend hundreds of hours teaching students how to handle cargo operations, fires, and emergency procedures. Yet, we spend almost zero hours teaching them how to manage emotional burnout, or how to set professional boundaries in a confined space.

However, this paper is not about pointing out flaws. We will discuss how universities can evolve their curriculum by integrating practical psychological preparation. We will explore the benefits of introducing mandatory soft skills training, focusing heavily on emotional intelligence and conflict resolution.

The ultimate goal of this research is clear. If we want these young women to stay in the commercial maritime industry and eventually become captains or chief engineers, we need to give them the right tools. We need to prepare their minds just as rigorously as we prepare their technical skills.

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1.1 Motivation for choosing the topic

The motivation for this research stems from a persistent "diversity paradox" within the maritime industry: the disconnect between the successful campaigns to enroll young women in maritime universities and the harsh reality of shipboard life that often drives them to leave the industry early.

I chose this topic to investigate why the commercial vessel, during the crucial first voyage, often functions as an environment of social isolation rather than a space for professional integration.

Furthermore, this paper aims to move beyond the simplistic debate of telling young women to simply "toughen up" in a male-dominated field. By acknowledging the demanding technical realities of the sea while using sociological and psychological frameworks to highlight the risks of hyper-visibility and emotional burnout, I hope to provide a balanced analysis.

Ultimately, the goal is to show that improving female retention in the global fleet requires a transition from purely technical training to a system that actively addresses the human element and psychological preparedness.

1.2 Research objectives

The primary goal of this research is to analyze the tension between the rigorous technical preparation provided by maritime academies and the glaring lack of psychological support for female cadets. To achieve this, the paper pursues the following objectives:

O1. Analyse the Culture: To examine the deeply ingrained social dynamics and unwritten rules of the commercial shipping environment, specifically focusing on how gender biases operate in confined spaces.

O2. Evaluate the Psychological Impact: To investigate how the first voyage affects the mental well-being of female cadets, utilizing concepts such as "hyper-visibility" and the "burden of representation" to understand emotional exhaustion.

O3. Propose Solutions: To identify the key elements of an updated educational paradigm, such as mandatory soft skills training, emotional intelligence modules, and mentorship programs that are essential for a successful and sustainable career at sea.

1.3 Working hypotheses

H1. While maritime universities excel at providing the necessary technical and navigational training, the complete absence of structured psychological preparation leaves female cadets highly vulnerable to social isolation and early career burnout.

H2. The commercial shipboard environment acts as a magnifying glass for gender dynamics; rather than blending in as junior trainees, female cadets experience a state of "hyper-visibility" that forces them to constantly overcompensate.

H3. There is a significant implementation gap between international policies promoting maritime diversity and the actual curriculum taught in universities, rendering these diversity goals fragile unless supported by concrete emotional and psychological training.

2. THE SHOCK OF THE FIRST VOYAGE (EXPECTATIONS VS. REALITY)

Getting accepted for that first cadetship contract is a huge milestone. For a female maritime student, it feels like the ultimate reward after years of studying intense technical subjects. The bags are packed, the medical checks are cleared, and everyone back home is incredibly proud. But the moment she boards and the heavy steel doors close, the commercial vessel stops being a theoretical concept. It becomes a massive, isolated industrial plant, and the safety net of the university is completely gone.

The hardest part of this transition is rarely the actual work. Universities do a brilliant job preparing students for the gruelling shifts, the deafening engine noise, or the stress of a navigational watch.

Instead, the true shock is overwhelmingly social and psychological. When a young woman steps on board a commercial ship, she rarely blends in. She stands out immediately, whether she wants to or not.

This specific dynamic is actually a well-documented issue in modern maritime sociology. Dr. Momoko Kitada, a leading expert from the World Maritime University, has written extensively about the unique shipboard culture that female seafarers face. According to her studies, women at sea often live in a state of "hyper-visibility" [4].

In simple terms, this means a female cadet is constantly under a microscope. If a male cadet makes a mistake while plotting a route or turning a valve, the crew usually brushes it off as a normal rookie error. However, if a female cadet makes the exact same mistake, it is frequently used as unfair proof that women simply do not belong at sea [5].

Because of this constant spotlight, female cadets experience what sociologists call the "burden of representation." Research conducted by the Seafarers International Research Centre (SIRC) points out a painful reality: young women on ships often feel the intense need to work twice as hard just to be considered half as good by their male superiors [8]. The mental energy required to keep up this flawless professional mask every single day is completely exhausting.

Furthermore, we have to remember that a commercial ship is a home for four to six months. The isolation these young women feel is not just about being far from land; it is about feeling socially disconnected from the rest of the crew. The informal culture on board, such as the inside jokes in the mess room or the traditional "boys' club" mentality, can be incredibly lonely for an outsider.

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Even though the International Maritime Organization (IMO) is pushing massive global campaigns to integrate women into the industry [1], the reality on the deck remains tough. This constant state of high alert drains a cadet's emotional batteries long before physical fatigue ever sets in. It creates a massive vulnerability, and unfortunately, it is something our current educational system completely overlooks.

3. THE ROLE OF PEER SUPPORT AND DIGITAL CONNECTIVITY

In the past, a cadet embarking on their first voyage was truly cut off from the world, with only occasional letters or expensive satellite calls to bridge the gap. For today's generation of female cadets, however, the psychological landscape has shifted due to digital connectivity. While the physical isolation on board remains a reality, the ability to access "digital lifelines" has become a vital survival mechanism.

When a female cadet feels the weight of "hyper-visibility" or faces a difficult social interaction on deck, her first instinct is often to reach out to her peers, such as other female students or junior officers who are undergoing the exact same experience.

Whether it is through dedicated WhatsApp groups, Instagram communities, or forums, these digital spaces provide a "psychological safe zone." In these networks, cadets can vent their frustrations and realize that their struggles are not personal failures, but systemic challenges shared by many others. This peer validation is often the only thing that prevents a cadet from quitting during a particularly tough first month.

However, this digital connection is a double-edged sword. Research into maritime mental health suggests that while social media provides support, it can also increase the feeling of "FOMO" (fear of missing out) and intensify homesickness by constantly showing the contrast between a cadet's industrial reality and her friends' normal lives back home [7].

4. EVOLVING THE PARADIGM: SOFT SKILLS AND MENTORSHIP AS ANCHORS OF RESILIENCE

If the industry truly wants to retain female talent, the conversation must shift from simply getting women on board to ensuring they thrive once they are there. This requires an evolution in the maritime educational paradigm. Universities must expand their focus beyond technical proficiency and begin treating psychological preparedness as a critical safety requirement.

To bridge the gap between the safe lecture hall and the harsh reality of the deck, two strategic solutions stand out:

- the formal integration of soft skills training
- the establishment of structured mentorship programs.

First, "soft skills" should no longer be viewed as optional corporate buzzwords, but rather as essential survival tools in a confined environment. A female cadet needs to be explicitly taught how to set firm professional boundaries, how to de-escalate interpersonal conflicts, and how to protect her mental health when facing subtle biases.

Incorporating modules on emotional intelligence and stress management directly into the mandatory university curriculum would give young women the vocabulary and the confidence to handle the "burden of representation" without internalizing the stress. According to organizational psychologists, equipping workers in isolated environments with emotional regulation techniques drastically reduces early career burnout [6].

Second, universities possess a massive, untapped resource: their own returning students. One of the most effective ways to combat the profound isolation of the first voyage is to establish a female-to-female mentorship pipeline. An academic program that pairs a second-year student who is about to leave for her first contract with a fourth-year student who has recently returned from sea would be transformative.

Guidelines developed by the International Transport Workers' Federation (ITF) highly recommend mentoring networks for female seafarers, noting that shared experiences demystify shipboard life and provide a crucial psychological safety net [3].

Through these university-facilitated connections, a departing cadet learns the unwritten rules of the ship not through painful trial and error, but through the guidance of someone who has successfully navigated the exact same waters.

Ultimately, by pairing world-class technical education with mandatory psychological preparation, we can equip the next generation of female officers with both the navigational tools to cross the oceans and the emotional compass to build lasting, successful careers at sea. Providing this support is the only way to ensure that a woman's first voyage marks the beginning of a lifelong journey, rather than a reason to leave the industry.

5. CONCLUSIONS

The analysis shows that, for female cadets, the first voyage is primarily a social and psychological test rather than a technical one. The arguments presented support the three working hypotheses: maritime universities provide solid technical training but little structured psychological preparation (H1); the shipboard environment exposes female cadets to hyper-visibility and to the burden of representation, which leads to constant overcompensation and emotional exhaustion (H2); and international policies promoting gender diversity are not yet matched by corresponding content in the curriculum (H3). Although the STCW framework [2] already includes elements of personal safety and

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social responsibility, these are treated briefly and do not address the specific pressures faced by women in predominantly male crews.

Digital peer networks currently act as an informal support mechanism, but they cannot replace institutional preparation. The paper therefore recommends two measures that maritime universities can implement within existing programmes: mandatory soft skills modules focused on emotional intelligence, stress management, conflict de-escalation and professional boundary setting, and a structured mentorship programme pairing cadets preparing for their first contract with senior students recently returned from sea. Future research should test these proposals empirically, through surveys and interviews with female cadets before and after their first voyage, in order to measure their effect on well-being and retention.

6. CREdit authors statement

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EDUCATIONAL STAND FOR PROGRAMMING AND CONTROL OF AN INDUSTRIAL PROCESS USING PLC AND HMI

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Abstract: This paper presents the design and implementation of an educational stand intended for programming and control of an industrial process using a Programmable Logic Controller (PLC) and a Human-Machine Interface (HMI). The proposed system aims to provide a practical learning platform for students in the field of industrial automation, enabling the development of essential skills in programming, configuration, and operation of modern control systems. The educational stand is based on an ABB AC500 PLC (PM573-ETH CPU), integrated with analog and digital input/output modules, communication modules, and an HMI panel for real-time monitoring and control. The system includes various industrial components such as actuators, control buttons, signaling devices, and measurement instruments, simulating real industrial conditions. The methodology involves the analysis of industrial automation principles, the design of the system architecture, hardware configuration, and the development of control software using the Automation Builder environment. Additionally, the HMI interface is designed to provide visualization of process parameters and user interaction capabilities. Experimental testing and validation of the system demonstrate its functionality under different operating scenarios. The results highlight the effectiveness of the proposed stand as a didactic tool for understanding PLC-based automation systems.
Key words: automation system, frequency converter, motor control, real-time monitoring, user interface

1. INTRODUCTION

Industrial automation plays a crucial role in modern production systems, ensuring increased efficiency, reliability, and safety. The use of Programmable Logic Controllers (PLC) and Human-Machine Interfaces (HMI) has become standard in industrial environments due to their flexibility and ability to control complex processes [1], [2], [6]. In technical education, it is essential to provide students with practical experience that complements theoretical knowledge [5], [7]. Educational stands that simulate real industrial processes represent an effective method for developing practical skills in automation [3], [4]. This paper presents the design and implementation of an educational stand for programming and control of an industrial process using a PLC and HMI. The main objective is to create a flexible and realistic platform for studying industrial automation systems.

2. SYSTEM ARCHITECTURE

The proposed educational stand is designed as a modular industrial automation system that integrates power supply, control, and user interface components.
The system is structured to simulate real industrial processes while providing a clear understanding of signal flow and control logic. The system includes a central PLC unit, input/output modules, and various field devices such as actuators and control elements [9].

The main components of the educational stand are illustrated in Figure 1. The power supply system (1) includes the MCB and the 12 V and 24 V DC sources. The PLC and I/O modules (2) represent the central control unit of the system. The control panel (3) includes push buttons, selector switches, potentiometers, and signalling lamps used for user interaction. The HMI interface (4) provides visualization and control of the process. Additionally, the system includes a DB connector (5) which allows external connections and integration with other systems and a serial communication interface (6).

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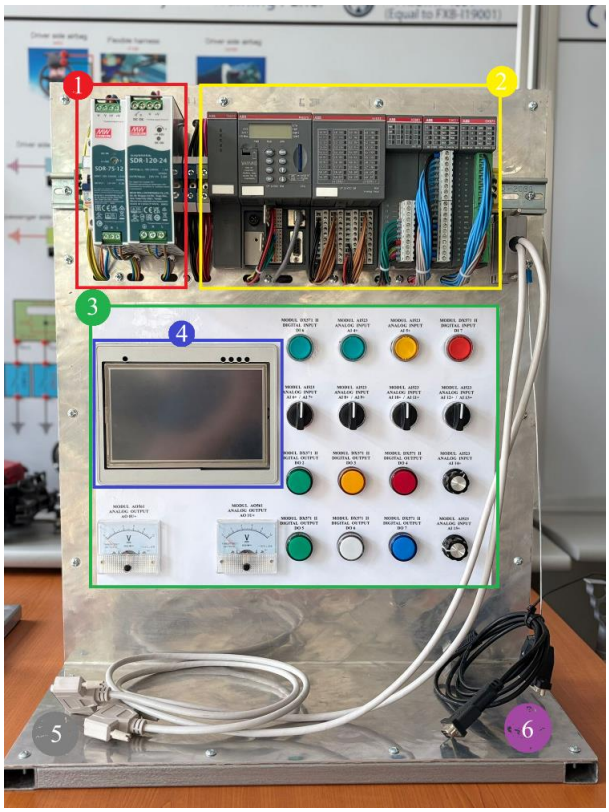


Figure 1 General view of the educational stand

3. HARDWARE IMPLEMENTATION

The hardware implementation of the educational stand is based on a modular structure that integrates power supply, control, and user interface components.

3.1 Power Supply System

The system is powered from a 230 V AC mains source, which is protected by a miniature circuit breaker (MCB). The power is then distributed to two stabilized power supplies manufactured by Mean Well, namely SDR-120-24 and SDR-75-12, which provide 24 V DC and 12 V DC, respectively. The 24 V DC source is used to supply the PLC, input/output modules, and control elements, while the 12 V DC source is dedicated to potentiometers and analogue adjustment components.

3.2 PLC and I/O Modules

The control system is built around an ABB AC500 programmable logic controller, specifically the PM573-ETH CPU, which acts as the central processing unit of the system.

To extend its functionality, the PLC is equipped with several input/output modules, including DX571 digital input/output modules, AI523 analogue input modules, and AO561 analogue output modules. These modules allow the system to interface with both digital and analogue signals, enabling the implementation of various industrial control scenarios [10], [11].

3.3 Control Panel and HMI

The educational stand includes a control panel equipped with push buttons, selector switches, signalling lamps, voltmeters, and potentiometers, allowing direct interaction with the system. Additionally, the system is equipped with an ABB CP635 B0 HMI panel, which provides real-time visualization and control of the process [13], [14].

3.4 Communication Interfaces

The system is equipped with communication interfaces that allow connection to external devices and systems. The PLC supports both serial and Ethernet communication [12]; however, the Ethernet interface is used in the current implementation for data exchange with the HMI and PC. Additionally, a DB connector is included to provide access to multiple input and output signals, enabling interconnection with other educational stands or external equipment.

4. EXPERIMENTAL SETUP

The experimental setup consists of the developed educational stand interconnected with an external training system and a frequency-controlled motor, as shown in Figure 2.

The experimental setup presented in Figure 2 consists of the developed educational stand interconnected with an external training system. The developed stand (1) represents the main control unit based on the ABB AC500 PLC and associated input/output modules, responsible for processing signals and executing the control logic. The connection between the two systems is achieved through a DB connector (2), which enables signal exchange between the developed stand and the external system. The external system (3) integrates a Siemens SINAMICS G110 frequency converter. Additionally, a three-phase motor (4) simulates the main load of the industrial process.

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Figure 2 Experimental setup including the developed stand, frequency converter and motor

5. PLC PROGRAMMING AND HMI

The control logic of the system was developed in the ABB Automation Builder environment using the Structured Text (ST) language [2], [8]. The main program, PLC_PRG, manages both the operating modes of the stand and the interaction with the external training system and the frequency converter. The software structure is based on two main operating modes, namely HMI mode and stand mode. The selection between these modes is performed through dedicated switches. In HMI mode, the process is controlled through parameters introduced from the operator interface, while in stand mode the operation is performed directly from the physical control elements mounted on the stand, such as push buttons, switches, and potentiometers. In HMI mode, the program executes a predefined speed profile for the controlled motor. The sequence is divided into several time intervals corresponding to acceleration, steady operation, deceleration, and direction change. The frequency reference is calculated step by step according to the selected values for positive and negative speed, cycle number, and segment duration. This operating principle allows the implementation of a bidirectional motion profile, displayed graphically on the HMI interface.

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Figure 3 HMI screen with motion profile

The motion profile shown on the HMI is defined through parameters such as tp1, ta1, ts1, td1, tp2, ta2, ts2, and td2, which represent the timing of each operating segment. Based on these values, the PLC calculates the output frequency and transmits the corresponding analog command to the frequency converter. The output signal is generated through the analog output channel AO_CH1, scaled according to the selected maximum frequency.

In stand mode, the motor can be controlled directly from the panel elements. The start and stop commands are received either from push buttons or from selector switches, depending on the selected operating configuration. The direction of rotation can be set to direct or reverse, while the frequency reference can be selected either from fixed levels or through potentiometer adjustment. The ramp time is also configurable using analog input signals, allowing a gradual variation of the output frequency.

The program also includes signal processing for status indication through signaling lamps. Depending on the operating condition, the system activates different lamps to indicate forward operation, reverse operation, stop condition, speed range, or ramp selection. This improves the visibility of the process state during laboratory operation.

The HMI interface was configured to provide real-time monitoring and intuitive control of the system. It allows the user to set the operating parameters, visualize the motion diagram, and start or stop the controlled sequence. The integration between the PLC program and the HMI interface ensures efficient supervision of the process and improves the educational value of the stand.

6. RESULTS AND TESTING

The developed system was tested under real operating conditions in order to validate its functionality. The experimental setup consists of the developed educational stand interconnected with an external training system and a frequency-controlled motor. As shown in Figure 4, the motion profile displayed on the HMI corresponds accurately to the motor behavior.

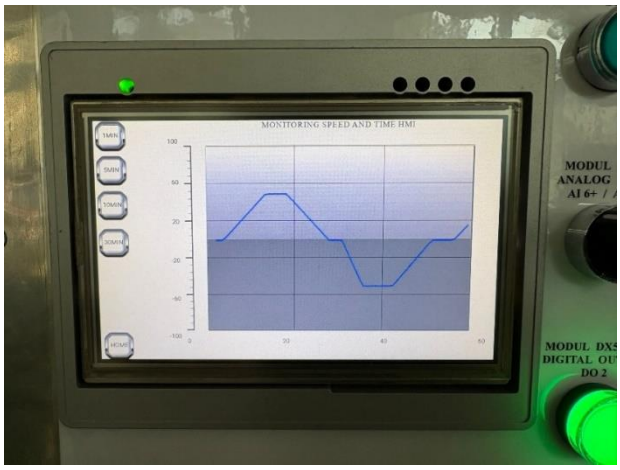


Figure 4 HMI visualization of the motor speed profile during operation

The experimental results confirmed the correct operation of the control system. The PLC successfully

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processed input signals and generated appropriate output commands, ensuring proper control of the frequency converter and motor operation. The implemented motion profile was accurately executed, with smooth transitions between speed levels and correct switching between forward and reverse directions.

The HMI interface provided real-time monitoring of the system parameters and allowed intuitive user interaction. The displayed motion diagram corresponded to the actual behavior of the motor, confirming the correct implementation of the control algorithm. The system demonstrated stable operation, reliable communication between components, and consistent response to control commands, proving its suitability for educational and training purposes in the field of industrial automation.

7. CONCLUSIONS

This paper presented the design and implementation of an educational stand for programming and controlling an industrial process, built around an ABB AC500 PLC (PM573-ETH CPU), digital and analog input/output modules and an ABB CP635 HMI panel. The stand reproduces the main elements of a real automation system, namely power distribution, control logic, field devices, operator interface and communication with external equipment, in a compact and modular structure suitable for laboratory use.

The tests carried out with the external training system, the SINAMICS G110 frequency converter and the three-phase motor confirmed the correct operation of both operating modes: in HMI mode, the predefined speed profile was executed with smooth transitions between segments, while in stand mode the motor was controlled directly from the panel elements, including the direction of rotation, the frequency reference and the ramp time. The correspondence between the motion diagram displayed on the HMI and the actual behaviour of the motor shows that the stand can be used to teach PLC programming in Structured Text, analog signal scaling and frequency converter control. Future developments may include the use of the serial and DB interfaces for interconnection with other educational stands, the integration of additional industrial communication protocols and the development of a set of laboratory exercises with progressive difficulty.

8. CREdit authors statement

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THE ECONOMICS OF DRONE LOGISTICS AND FREIGHT DELIVERY CASE STUDY:IMPLEMENTATION OF A DRONE DELIVERY SYSTEM IN CONSTANȚA

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Abstract: The rapid expansion of e-commerce has increased demand for efficient, reliable and sustainable last-mile delivery. This paper evaluates the economic and operational feasibility of an illustrative drone delivery system for Constanța, Romania, using Cargus as a hypothetical implementation context rather than describing an existing company project. The study applies a scenario-based cost comparison between conventional couriers and autonomous air deliveries. Its assumptions include a total investment of EUR 20 million, a drone acquisition allocation of EUR 9.6 million, a unit acquisition price of EUR 20,100, ten operating hours per day and a twenty-minute average delivery cycle. Under these assumptions, 477 drones could theoretically complete 14,310 delivery cycles per day before accounting for charging, weather, airspace restrictions, payload limits and demand. At assumed costs of EUR 5–10 for conventional delivery and EUR 1–2 for drone delivery, the illustrative gross daily cost difference ranges from EUR 42,930 to EUR 128,790 when comparing the respective cost extremes. These figures do not constitute verified savings or a financial forecast because operating availability, staffing, depreciation, energy and regulatory compliance costs require further validation. The analysis identifies potential benefits in time-sensitive distribution while highlighting airspace safety, infrastructure, reliability and investment risks. It concludes that a phased pilot and a detailed regulatory and financial assessment are prerequisites to any commercial deployment.

Key words: autonomous delivery; cost analysis; drone logistics; last-mile delivery; urban transport.

1. INTRODUCTION

The paper entitled "The Economics of Drone Logistics and Freight Delivery" analyses the economic, operational, and technological impact of using drones in logistics and freight transportation, in a context where e-commerce and the demand for fast deliveries continue to grow rapidly [1]. The development of autonomous technologies and artificial intelligence has led to the emergence of new transportation models, and drones represent one of the most innovative solutions for optimizing urban logistics processes [2-4].

In recent years, international courier and transportation companies have started investing in autonomous delivery systems in order to reduce operational costs, decrease delivery times, and improve the efficiency of services provided to customers. Compared to traditional distribution methods, drone delivery offers significant advantages such as avoiding urban traffic congestion, reducing fuel consumption, automating operations, and enabling rapid delivery of urgent or lightweight products [5-7].

This paper aims to highlight both the economic advantages of drone-based logistics and the challenges associated with implementing this technology. The study analyses the possibility of implementing an autonomous delivery system in Constanța within Cargus by evaluating the required investments, operational capacity, and economic profitability of the project [7-8].

The paper compares the costs of traditional courier systems with autonomous drone deliveries while also examining the impact on logistics infrastructure, consumers, and the future development of intelligent transportation systems. In addition, aspects related to scalability, maintenance, reliability, and the adaptability of drone systems during high-demand periods such as Black Friday and public holidays are presented.

Through this analysis, the study aims to demonstrate that drone-based logistics can represent a viable and sustainable solution for the future of urban deliveries, with the potential to significantly transform the transportation and courier industry [1-.

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2. CONTEXT AND OBJECTIVES OF THE CASE STUDY

In order to evaluate the practical applicability of drone logistics, this case study analyses the implementation of an urban drone delivery system at the company Cargus in the city of Constanța, Romania.

Constanța represents a suitable environment for such an implementation due to: its medium urban density; existing logistics infrastructure; increasing demand for e-commerce deliveries; relatively manageable geographic area.

The main objectives of this case study are: to determine the operational capacity of a drone delivery system; to evaluate its economic efficiency; to compare it with traditional delivery methods; to assess its feasibility in the Romanian context.

3. INVESTMENT PARAMETERS AND INVESTMENT STRUCTURE

The implementation of the system requires an initial investment, structured as follows:

- Total budget: €20,000,000
- Drone budget: €12,000,000
- Cost per drone DJI FlyCart : €20,100
- Allocation for infrastructure and operational costs (20%): €2,400,000

(20% x 12,000,000 = 2,400,000 €)

- Remaining budget for drone acquisition:

€9,600,000 =12,000,000-2,400,000.

Number of drones:

$$9{,}600{,}000 \div 20{,}100 \approx 477 \text{ drones;}$$

20,100 x 477 = 9,587,700 €

Thus, the system includes approximately 477 operational drones.

- *Urban infrastructure and logistics* –€ 5,000,000: urban hubs; take off/landing platforms; hangars, charging stations; security, cameras, operational spaces.

- *Software and staff training* – €2,000,000: fleet management platform; AI, route optimization; real-time monitoring.

- *Licenses and insurance* – €1,000,000

Types of licenses: Urban UAV operation license; Communications license; AI and fleet management software license.

Types of insurance: Third-party liability; Drone and equipment insurance; Transported goods insurance.

- *Organizational Structure*.

Total: 42 employees

- 10 drone maintenance technicians
- 15 control and surveillance operators
- 10 logistics and coordination staff
- 7 IT, software, and AI specialists

4. OPERATIONAL CAPACITY

Each drone operates under the following conditions: operational time of 10 hours/day and average delivery cycle of 20 minutes.

Deliveries per drone:

$$(60/20) \times 10 = 30 \text{ deliveries/day.} \quad (1)$$

Total system capacity:

$$477 \times 30 = 14{,}310 \text{ deliveries/day.} \quad (2)$$

This represents a significant delivery capacity for an urban environment.

5. OPERATIONAL MODEL OF DRONE DELIVERY

The drone delivery process is fully automated and consists of:

- Order placement via digital platform
- Automatic drone allocation
- Route optimization using AI
- Package loading at logistics hub
- Autonomous delivery
- Digital confirmation of delivery

This system minimizes human intervention and increases operational efficiency.

6. ANALYSIS OF TRADITIONAL DELIVERY SYSTEMS

Traditional courier services rely on: vehicle fleets; human couriers; road infrastructure.

Estimated operational parameters:

- -Deliveries per courier: 80–120 parcels/day,
- -Working time: 8–10 hours/day.

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Identified issues: traffic congestion; delivery delays; failed deliveries (10–15%); high operational costs.

7. COST ANALYSIS: TRADITIONAL VS. DRONE DELIVERY

- Traditional delivery: Cost per delivery- €5–10
- For 14,310 deliveries: €71,550 – €143,100 per day
- Drone delivery: Cost per delivery: €1–2
- For the same volume: €14,310 – €28,620 per day .

COST SAVINGS

- Daily savings: between €57,000 and €114,000
- Annual savings: between €20 million and €40 million .

This demonstrates a significant economic advantage of drone-based logistics.

REVENUE MODEL

A premium fast-delivery service is introduced.

- Additional fee: €1.5 per delivery
- Daily revenue: $14{,}310 \times 1.5 = 21{,}465€$
- Annual revenue: approximately €7.7 million

INVESTMENT PAYBACK PERIOD

- Total investment (extended system): €20,000,000
- Payback period: $20{,}000{,}000 \div 7{,}700{,}000 \approx$ 2.6 years

This indicates a fast return on investment.

8. SEASONAL DEMAND AND PEAK PERIOD ANALYSIS

During peak periods such as: holidays (Christmas, Easter); Black Friday. The volume of deliveries increases by 50% to 200%.

Challenges for traditional systems: overloaded couriers; delayed deliveries; parcels redirected to warehouses; customers forced to pick up packages themselves [8-10].

Advantages of drones in peak periods: scalable operations (multiple drones simultaneously); faster processing of urgent deliveries; reduced pressure on traditional logistics systems.

COMMONLY DELIVERED PRODUCTS

Drone delivery is suitable for lightweight and urgent goods such as: pharmaceuticals (medications); food products; small electronics; baby care products; urgent documents.

BENEFICIARY CATEGORIES

Drone delivery is particularly beneficial for:

1. Parents with young children: need for urgent supplies, limited mobility;

2. Elderly people: reduced mobility, frequent need for medication;

3. People with disabilities: difficulty accessing physical stores;

4. Urban professionals: limited time availability, preference for fast delivery.

FEASIBILITY IN ROMANIA

Currently, drone delivery is not widely implemented in Romania; regulations are still evolving.

There are opportunities, such as: first-mover advantage; technological innovation; improved logistics efficiency.

Drone systems offer: high reliability through automation; reduced mechanical failure risk; predictive maintenance capabilities.

Compared to traditional systems: lower maintenance costs; fewer operational disruptions.

Our analysis demonstrates that: drone delivery is significantly more cost-efficient; delivery times are considerably reduced; operational scalability is improved; investment recovery is rapid.

9. CONCLUSIONS

In conclusion, the paper highlights that the use of drones in logistics and freight transportation represents a modern and efficient direction for the development of urban delivery services. The analysis demonstrates that implementing an autonomous drone delivery system in Constanța within Cargus can generate significant economic and operational advantages compared to traditional distribution methods.

From an economic perspective, the analysed investment proves to be profitable, with an estimated payback period that is relatively short compared to the financial benefits and annual operational savings generated. In addition, the implementation of this system can contribute to the modernization of urban logistics infrastructure and increase the competitiveness of courier companies in the fast-delivery market.

However, the development of drone-based logistics depends on the evolution of the legislative framework, air safety regulations, and the adaptation of urban infrastructure to new autonomous technologies. Although this technology is still at an early stage in

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Romania, the study demonstrates a strong potential for the future implementation of drone delivery systems.

Therefore, drones can represent a sustainable and innovative solution for the future of urban transportation, contributing to the optimization of logistics chains and transforming the way commercial deliveries are carried out in urban environments.

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CYBERATTACKS ON MARITIME PORT INFRASTRUCTURE: THREAT LANDSCAPE AND RESILIENCE STRATEGIES

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Abstract: Maritime port infrastructure represents one of the most critical and increasingly targeted categories of critical infrastructure in Europe. Ports such as Constanta — Romania's largest seaport and the busiest on the Black Sea — concentrate extensive digital systems managing cargo operations, customs processing, navigation, and supply chain logistics, creating a complex attack surface that adversarial actors have increasingly exploited through ransomware, operational technology attacks, and data breaches. This paper examines the evolving threat landscape facing maritime port infrastructure, analyses the specific vulnerability profiles of port digital systems, and evaluates the resilience frameworks required to protect these critical assets. Drawing on documented incident analysis and the requirements of the EU NIS2 Directive and ISPS Code, the paper proposes a four-layer resilience architecture that addresses governance, detection, protection, and response simultaneously.

Key words: maritime cybersecurity, port infrastructure, ransomware, OT security, NIS2, critical infrastructure.

1. INTRODUCTION

Maritime ports are the backbone of global trade, processing approximately 90% of international cargo by volume and generating economic value that makes them among the highest-priority critical infrastructure assets in any coastal nation. Constanta Port, handling over 60 million tonnes of cargo annually and serving as the primary gateway for Central European trade with the Black Sea and beyond, exemplifies both the economic significance and the cybersecurity exposure of major maritime port facilities. The digital systems that enable modern port operations — cargo management platforms, customs IT systems, SCADA-controlled cranes and loading equipment, vessel traffic management systems, and access control networks — collectively present an attack surface of extraordinary complexity that has attracted growing adversarial attention from both criminal and state-sponsored threat actors [1].

The trajectory of cyberattacks targeting maritime port infrastructure, illustrated in Figure 1, reveals a threat landscape that has intensified significantly since 2019 and accelerated further following Russia's invasion of Ukraine in 2022. Ransomware incidents, data breaches, and operational technology attacks have all grown at rates that exceed the general cybersecurity incident trajectory, reflecting both the increasing attractiveness of port infrastructure as a high-value target and the structural vulnerabilities that legacy operational technology systems create in an environment where cyber threats were not historically considered in system design [2].

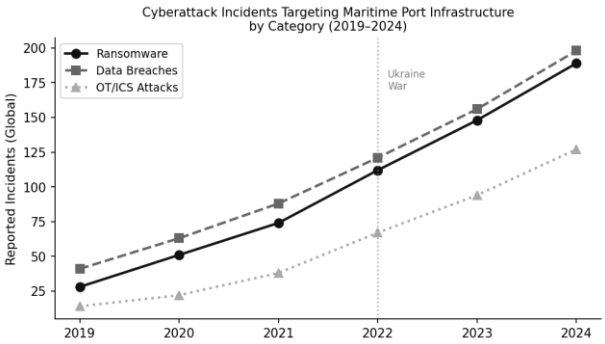


Figure 1 Cyberattack incidents targeting maritime port infrastructure by category (2019–2024). [1]

All three major attack vectors show sustained growth, with OT/ICS attacks showing the steepest relative increase — rising ninefold over the period. [1]

2. DOCUMENTED INCIDENT CASE STUDIES

The empirical record of cyberattacks on port infrastructure provides compelling evidence of both the diversity of threat vectors and the severity of operational consequences that successful attacks can produce. The 2017 NotPetya attack on Maersk — while not targeting port infrastructure directly — caused the shutdown of 17 Maersk port terminals globally, disrupting approximately

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300 million tonnes of cargo handling capacity and costing an estimated $300 million in recovery costs and lost business. The incident demonstrated the cascading consequence potential of cyberattacks on interconnected maritime logistics systems: a single malware propagation event triggered a global operational paralysis that required weeks to resolve [2].

The 2021 ransomware attack on the Port of Houston provided a closer analogue to the specific threats facing European port infrastructure. Attackers used spear-phishing to gain initial access to the port's IT network, subsequently deploying ransomware that encrypted critical cargo management data and disabled multiple operational systems. While rapid incident response limited the operational impact, the attack revealed the inadequacy of network segmentation between IT and OT environments, which would have prevented malware propagation from administrative systems to operational technology controlling physical port infrastructure [3].

European ports have not been immune. The 2022 cyberattacks targeting oil terminal operators in Belgium, Germany, and the Netherlands — coinciding with the Ukraine conflict's disruption of energy supply chains — demonstrated the potential for geopolitically motivated actors to target maritime logistics infrastructure as an instrument of hybrid warfare. For Constanta Port, whose strategic significance has increased substantially in the context of its role as a transit hub for aid and military supplies to Ukraine, this threat dimension carries particular operational relevance.

3. VULNERABILITY ANALYSIS OF PORT DIGITAL SYSTEMS

Figure 2 presents vulnerability scores and security update rates for six categories of port digital systems, revealing a consistent and concerning pattern: the systems with the highest vulnerability scores — SCADA/ICS (84), communication networks (78), and cargo management (72) — also show the lowest patch and update rates (31%, 44%, and 48% respectively). This inverse relationship reflects the operational constraints of port environments: SCADA and ICS systems controlling physical infrastructure cannot be taken offline for updates during operational hours without disrupting cargo handling, and the extended update cycles that result create accumulating vulnerability exposure that adversaries actively probe [3].

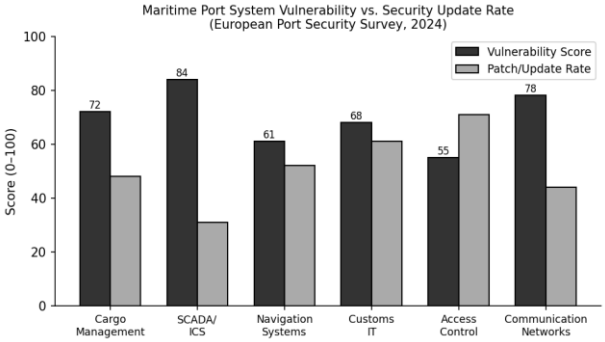


Figure 2 Vulnerability score vs. security update rate for six port system categories. [2]

The inverse relationship — highest-vulnerability systems showing lowest update rates — reflects the operational constraints of port environments and represents the central challenge for port cybersecurity management. [2]

The SCADA/ICS vulnerability profile deserves particular attention given its potential for physical consequence. Unlike IT systems whose compromise typically produces data and operational disruptions, OT system compromise can translate directly into physical damage: compromised crane control systems, manipulated container tracking, falsified weight measurements, or disrupted vessel traffic management can produce consequences ranging from cargo damage to vessel collisions. The 2021 Oldsmar water treatment facility attack — in which an attacker remotely accessed a SCADA system and attempted to increase chemical dosing to dangerous levels — illustrates the physical harm potential of OT system compromise in critical infrastructure contexts [4].

Communication network vulnerabilities create a second critical exposure category. Port operations depend heavily on real-time data exchange between vessels, terminals, customs authorities, and logistics partners, creating extensive network connectivity that expands the attack surface beyond the port's own perimeter. Software-defined radio systems used for vessel communications, AIS transponder networks, and port community systems connecting multiple stakeholders all represent entry vectors through which adversaries can gain initial access to port networks. The vulnerability score of 78 for communication networks combined with a 44% update rate suggests that this attack surface remains inadequately secured in most European port contexts.

4. RESILIENCE FRAMEWORK

Effective cybersecurity for maritime port infrastructure requires a comprehensive resilience architecture that addresses the threat landscape across four integrated layers, as presented in Figure 3. No single-layer approach — whether focused exclusively on technical protection, detection capability, or incident

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response — can adequately address the complexity and adaptability of the threat actors targeting port infrastructure. The four-layer framework integrates governance, detection, protection, and response into a coherent system in which each layer reinforces the others.

The four-layer architecture ensures that governance requirements drive technical implementation, detection capability enables early threat identification, protection measures reduce attack surface, and response/recovery capabilities minimize harm when attacks succeed. Author's model based on ENISA Port Cybersecurity Guidelines [5].

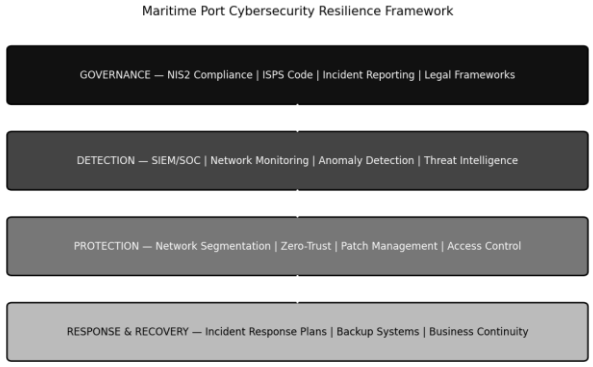


Figure 3 Maritime port cybersecurity resilience framework. [5]

The governance layer establishes the legal and organizational foundation for all other resilience activities. The EU Network and Information Security Directive (NIS2), which entered full application in October 2024 and classifies major maritime ports as essential entities subject to mandatory cybersecurity requirements, provides the primary legal framework. NIS2 requires essential entities to implement appropriate technical and organizational risk management measures, establish incident reporting procedures, and maintain business continuity plans — creating enforceable minimum standards that address the governance deficits historically characteristic of port cybersecurity. The International Ship and Port Facility Security (ISPS) Code provides a complementary framework specifically tailored to maritime security contexts, while the IMO's Maritime Cyber Risk Management guidelines offer operational guidance for vessel and port system risk assessment.

The protection layer translates governance requirements into technical implementation. Network segmentation — creating isolated network zones for IT, OT, and externally connected systems with strict controls on inter-zone traffic — is the single most impactful technical control available for reducing the blast radius of successful intrusions. Zero-trust architecture principles, which eliminate the implicit trust assumptions that allow lateral movement within networks once initial access is achieved, provide a complementary approach particularly valuable for port community systems where multiple external organizations require network access. Patch management programs that accommodate the operational constraints of OT environments — through scheduled maintenance windows, virtual patching, and compensating controls for systems that cannot be updated — address the update rate gap identified in the vulnerability analysis.

5. IMPLICATIONS FOR CONSTANTA PORT AND ROMANIAN CRITICAL INFRASTRUCTURE

Constanta Port's elevated strategic significance in the current security environment — serving as a primary logistics hub for aid and military equipment transiting to Ukraine while simultaneously handling record cargo volumes driven by the rerouting of Black Sea trade — makes it a priority target for both criminal ransomware actors and state-sponsored threat actors with interest in disrupting NATO logistics flows. The port authority's cybersecurity investments must reflect this elevated threat profile, not the baseline risk assessment appropriate for a peacetime commercial port environment.

The Romanian National Directorate of Cyber Security (DNSC) has identified maritime port infrastructure as a priority critical infrastructure category under Romania's NIS2 implementation framework, designating Constanta Port as an essential entity subject to the Directive's enhanced requirements. Compliance with these requirements — including the mandatory risk management measures, incident reporting within 24 hours of significant incidents, and regular security audits — provides the regulatory foundation for resilience development, but effective protection requires investment beyond the minimum legal standard given the specific threat profile that Constanta's strategic position creates [5].

6. CONCLUSIONS

Cyberattacks on maritime port infrastructure represent a growing, increasingly sophisticated, and strategically significant security challenge that demands systematic resilience investment from port operators, national authorities, and their European partners. The combination of high-value operational concentration, legacy OT system vulnerability, complex multi-stakeholder connectivity, and elevated adversarial interest creates a threat environment that incremental security improvements cannot adequately address. The four-layer resilience framework proposed in this paper — integrating governance, detection, protection, and response into a coherent, mutually reinforcing architecture — provides a structured approach to closing

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the most critical vulnerability gaps identified in the European port cybersecurity landscape. For Constanta Port and Romanian critical infrastructure authorities, the urgency of this investment is compounded by the current geopolitical environment: the window for orderly resilience development before a significant incident occurs may be shorter than comfortable planning timelines allow.

7. CREdit authors statement

Conceptualization: P.D.; Data curation: P.D.; Formal analysis: P.D.; Funding acquisition: not applicable; Investigation: P.D.; Methodology: P.D.; Project administration: P.D.; Resources: P.D.; Software: not applicable; Supervision: not applicable; Validation: P.D.; Visualization: P.D.; Writing – original draft: P.D.; Writing – review & editing: P.D..

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IGNITION EXPERIMENTS AND SIMULATIONS OF AQUEOUS AMMONIA AND HYDROGEN PEROXIDE MIXTURES IN A DIESEL ENGINE

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Abstract: This work provides first experimental results of the use of ternary fuel blend consisting of ammonia (NH_3), water (H_2O) and hydrogen peroxide (H_2O_2) being used as carbonless diesel fuel blends in a conventional small-bore diesel engine. The work is aimed at identifying safe mixtures of fuels that contain zero carbon and that could replace current fossil fuels without requiring major engine replacements. Another important aspect of this work is that the fuels should be liquid at typical atmospheric conditions, so as to provide a safer alternative to gaseous ammonia and hydrogen for smaller marine applications. The results showed small but clearly visible heat release from the fuel decomposition in the engine following fuel injection. This could be replicated by simulations combining thermodynamic and chemical kinetic modelling. The simulation results showed promise that the results may be extended to different engine loads and different fuel injection timings, whilst achieving reliable fuel ignition. A life-cycle assessment (LCA) was conducted to analyse the potential benefits of using these carbonless fuel mixtures as a single fuel, compared to dual-fuel injection strategies using fossil diesel fuel as pilot injection and anhydrous ammonia as the main fuel. The LCA results showed that the mixture of NH_3 and H_2O_2 can reduce GWP100 by about 73.5% compared with conventional diesel, showing strong potential for reducing the climate impact of marine engines. However, further improvements in H_2O_2 production and fuel use are needed to reduce impacts in other environmental categories.

Keywords: Ammonia, Ammonium nitrate, Diesel Engine, Fuel, Water.

1. INTRODUCTION

The World Meteorological Organisation reported that the year 2025 was 1.44± 0.13 °C above the 1850-1900 average (WMO, 2026 [[1.]]), which is just short of the 1.5°C aim set out in the Paris Agreement (UNFCCC, 2016 [[2.]]). Shipping contributes around 3% of global greenhouse gas emissions (IMO, 2020 [[3.]]), which is expected to increase if not regulated appropriately. The final energy demand for shipping is expected to remain at around 10 EJ per annum for the foreseeable future, according to predictions up to 2050 (IMO, 2024 [[4.]]).

International shipping is a global industry and its emissions are regulated by the International Maritime Organization (IMO), which has set out its aim for net-zero greenhouse gas emissions by 2050 (IMO, 2023 [[5.]]), and is currently in the difficult process of trying to agree on a framework of globally binding regulations for meeting this aim (IMO, 2025 [[6.]]). Worldwide consensus on regulations is likely a key element for decarbonisation of international shipping, and such global consensus will be aided by the existence of accessible and cost-effective decarbonisation solutions. Many of the older vessels may not be easily retrofitted if a high capital expenditure is needed upfront to upgrade the engine and fuel system, which is why drop-in fuel solutions may be key to accelerating greenhouse gas reduction from shipping, by offering an accessible solution to older ships, and to those less-able to invest larger amounts of capital up-front.

Bio-fuels are currently the only drop-in fuels that can be used without any change in engine or fuel system. In practice these often end-up becoming the preferred option for older ships trying to reduce emissions, for which expensive technical upgrades may not be economically feasible. Biofuels are as of now amongst

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the cheaper options for reducing greenhouse gas emissions [[4.]], due to the low capital expense. At the same time, it is apparent that the supply of sustainable biomass is physically limited, and some LCA in the literature have shown that the consequences of increased biofuel production can in some cases lead to higher climate impacts than those from fossil fuels [[7.], [8.]].

The production of e-fuels such as hydrogen and ammonia, is one possible way of decoupling renewable fuel production from biomass resources. In the case of methanol, the production is still linked to the requirement for limited resources of biogenic CO_2, in order for the methanol to be sustainable. The use of CO_2 from direct air capture would be sustainable, but predictions for future costs of direct air capture of CO_2 estimates a cost range of 226-885 $/tCO2 [[9.]]. Even assuming the lowest cost scenario of 226 $/t$CO_2$ and assuming a calorific value of 21 MJ/kg of methanol, that would add a cost of 14.73 $/GJ, just for the captured CO_2 in future sustainable methanol. Aviation is also a competing sector, that arguably is in more dire need for carbon-based liquid fuels than shipping.

The trivial solution to avoiding the need for CO_2 as a feedstock for fuel productions is to use carbonless e-fuels. The challenge with the most prominent carbonless e-fuels hydrogen and ammonia is that both are gaseous at atmospheric pressure and common atmospheric temperatures, and are therefore more difficult to store. Hydrogen has the additional challenge of having a significant greenhouse gas impact itself (hydrogen GWP_{100} = 11±5 [[10.]]) and requiring very low temperature to be stored in liquid form (-253°C). Ammonia, although not having any climate impact itself, is toxic and gaseous at a pressure of 1 atmosphere and 20°C, and either requires cooling to -33.33°C at atmospheric pressure, or pressurising to around 1 MPa (at 25°C) to become liquid [[11.]]. If used as fuels in pure form, both hydrogen and ammonia require entirely different fuel systems and engine operational settings to work as fuels in marine diesel engines. Hydrogen and ammonia usually require an additional pilot fuel injection to ignite reliably in a diesel engine [[12.], [13.]].

Ammonia is a promising carbonless fuel, but for a broader success of its application, effective solutions for mitigating its toxicity risk and its difficulty to ignite in a diesel engine need to be found.

A potential solution is to use ammonia in a form that is liquid at room temperature. This can be achieved by using aqueous ammonia [[14.]], but also by blending ammonia with ammonium nitrate, to reduce the water content and improve its ignitability [[15.], [16.]]. To achieve the reliable ignition of ammonia, whilst at the same time ensuring that the physical mixture remains liquid at atmospheric pressure and typical atmospheric temperatures, it is necessary to study and measure the physical properties of ternary mixtures of ammonium nitrate, ammonia and water [[17.], [18.]]. Another chemical composition that is receiving interest by recent research, are the mixtures of ammonia with hydrogen peroxide (H_2O_2). The first study to examine the autoignition dynamics of hydrogen peroxide and ammonia mixtures diluted with water, was that of Khalil et al. (2020) [[19.]]. The first study to apply this mixture to engine applications was that of Frost et al. (2021) [[20.]]. Frost et al. (2021) found through simulation that it may be possible to remove the need for a pilot fuel injection in a diesel engine, if hydrogen peroxide was used as ignition improver in aqueous mixture with ammonia. Shafiq and Tingas (2022) [[21.]] carried out a systematic analysis of the performance of using ammonia and hydrogen peroxide (H_2O_2) with water dilution as fuel for Homogeneous Charge Compression Ignition (HCCI) engine applications, and reported significant influence of H_2O_2 as ignition improver and higher indicated mean effective pressure (IMEP) resulting from its use, compared with inlet air heating. Singh et al. (2022)[[22.]] investigated the effects of hydrogen peroxide on ignition delays and laminar flame speeds for premixed blends of ammonia, methane and air using chemical kinetic simulations. Single-fuel diesel-type engine combustion simulations for ammonia, hydrogen peroxide and water fuel mixtures in air where reported by Schönborn & Lee (2022)[[23.]]. Paterson et al. (2024)[[24.]] reported chemical kinetic engine simulations in which a pilot injection of 10% (vol.) hydrogen peroxide in water was used to help ignite fumigated fuel mixtures of ammonia and hydrogen (0.8 and 0.2 mole fraction respectively).

The literature thus provides quite a few studies of the use of hydrogen peroxide as ignition improver for ammonia as fuel, but apart from the studies by Frost et al. (2021)[[20.]], Schönborn & Lee (2022)[[23.]] the simulations used premixed combustion approaches. In the case of Paterson et al. (2024)[[24.]] this consisted of a hybrid approach using premixed ammonia and hydrogen in air as the main fuel, with a pilot fuel injection of hydrogen peroxide. A gap in the current literature is the lack of experimental studies, especially for non-premixed combustion, i.e. diffusion-controlled diesel combustion, which is the most reliable combustion mode for large marine engines.

The first works to provide experimental evidence for the use of hydrogen peroxide as ignition improver for ammonia, are the works of Han et al. (2024)[[25.]], followed by Hassan Ali & Ali (2024)[[26.]] and Han et al. (2025)[[27.]]. These investigations of Han et al. used a pilot injection of diesel fuel to provide a source of ignition, whilst the investigations of Hassan Ali & Ali (2024) analysed the ignition of homogeneously premixed blends of fuel in air, in HCCI engine operating mode.

The aim of this current work is to provide the first experimentally measured evidence of ignition for direct injection diffusion-controlled combustion, using liquid

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hydrogen peroxide, ammonia and water mixtures for a single-fuel approach. The direct injection diffusion-controlled combustion approach is the safest and most reliable way of operating large marine diesel engines, and is significantly different from other approaches such as HCCI, which have only practically been applied to small bore high-speed engines. The ultimate aim for the use of hydrogen peroxide as ignition improver would be to make a pilot fuel injection of conventional diesel fuel entirely redundant, and to thereby facilitate the transition from accepted high-pressure dual-fuel approaches, which typically still use conventional fossil fuels for a pilot injection, to high-pressure single-fuel approaches, using a liquid carbonless fuel. So far, no investigations with this aim have been reported in the literature.

2. MATERIALS AND METHDOS

Experiments were conducted using a direct injection generator engine with mechanical fuel pump and injector on a small-bore diesel engine (Lutian 5GF-LDE). The engine was turned-over electrically using the electrical starter motor of the generator, ensuring a constant engine speed of 165 ± 0.0 rpm during the tests used for this analysis. The engine cylinder pressure was measured at 10 000 Hz sampling frequency using a piezoresistive thin-film-on-steel pressure sensor (Trafag 8253) with a pressure range of 0...250 bar gauge and a pressure accuracy of ±0.3 % or 0.75 bar.

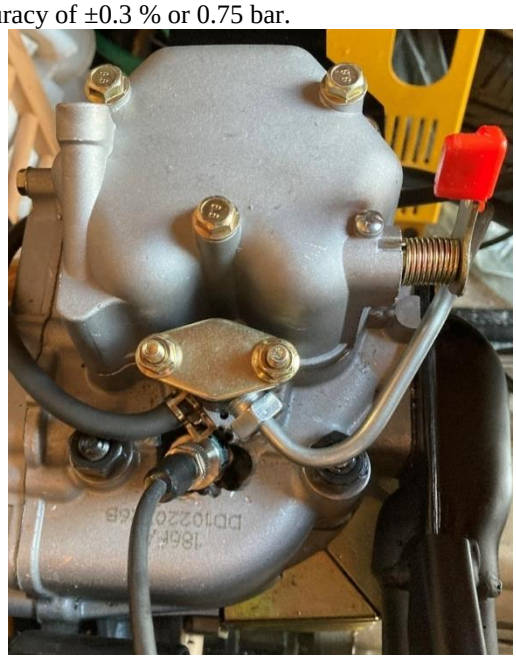


Figure 1. Test engine

The injection timing was set at 173° crank angle, i.e. 7° crank angle before top-dead-centre. The pressure sensor was fed using an 18V voltage supply and the 4-20 mA signal was acquired by measuring the voltage over a 470 Ohm resistor using a Labjack U3-LV time-triggered data acquisition system.

The fuel composition consisted of water, ammonia and hydrogen peroxide, in the molar fractions shown in Table 1.

Table 1. Fuel composition in mass fraction

Fuel blend number	NH_3	H_2O	H_2O_2
0	0.26	0.74	0.00
1	0.2314	0.74825	0.0204
2	0.2028	0.7565	0.0407
3	0.17	0.76	0.06

The fuel was prepared through volumetric blending of aqueous hydrogen peroxide (30% m/m) to the aqueous ammonia (25% m/m) using an open glass beaker. The mixture was delivered directly through a clean pipe to the fuel pump inlet using a gravity feed from a funnel from a 0.35 m height. The engine was operated either with the fuel injection switched on or with the fuel injection switched off, which was controlled using a mechanical switch. The experiments were repeated several times in various orders in order to verify the repeatability of the results.

2.1. Engine simulations

The experimental operation of the engine was compared with a thermodynamic and chemical kinetic model of the engine, which simulated the evolution of the molar composition, temperature and pressure of the air aspirated into the engine, as well as the fuel injected into the engine and the ensuing chemical reactions. This model assumed air being aspirated into the engine at a composition of 21% O_2, and 79% N_2, at atmospheric pressure and a temperature of 443 K, which was the temperature that could be reached in steady-state operation of the engine. The air was then compressed to around 3.3 MPa, assuming near-adiabatic compression, and at 179 degrees crank angle (i.e. 1 crank angle degree before top-dead-centre (TDC)) the fuel was injected into the engine. The fuel consisted of a ternary mixture of water, ammonia, and hydrogen peroxide, in the mole fractions given in

Table 1. The chemical reactions were simulated using the gas-phase chemical kinetic combustion model developed by Song et al. (2016) [[28.]].

A comparison of this chemical kinetic model with experimental results has been reported in an earlier work [[20.]].

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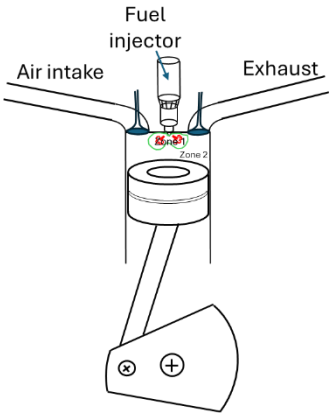


Figure 2. Schematic of engine simulation approach [20]

In order to reflect the different fuel-air stoichiometries present in a diesel engine, the engine was simulated using two reactor zones, which were spatially separated to have different stoichiometries of fuel and air, but the same pressure. These two zones were defined as Zone 1 (ignition zone) which had a fuel air stoichiometry close to unity, to represent the reactions taking place in the region around the fuel spray, and Zone 2 that represented the bulk gases within the engine, consisting of air.

2.2. LCA methods

The Life Cycle assessment (LCA) was carried out following the guidance and framework described in ISO14040 (ISO, 2006)[[34.]]. Assessing the life-cycle climate impact of the fuel is important in taking into account not only emissions during the The modelling was performed using LCA for Experts (version 10.9.3.0) software with data from the Eco invent database (version 3.8).

A simplified attributional LCA was carried out to compare the well to wake (WTW) environmental performance of three fuel scenarios:

(i) Diesel - using 100% conventional diesel fuel,

(ii) (ii) NH_3 & Diesel - using green ammonia and diesel as pilot fuel,

(iii) NH_3 & H_2O_2, using ammonia blending with hydrogen peroxide (**Error! Reference source not found.**).

Table 2. Fuel consumption in three scenarios

Scenarios	Items	Unit	Diesel	Ammonia	Hydrogen peroxide
	LHV	MJ/kg	43.10	18.60	1.5887
	Efficiency	%	51.00%	51.00%	51.00%
Diesel	% Energy share	%	100.00%	0.00%	0.00%
	Fuel consumption	g	163.78	0.00	0.00
NH_3 & Diesel	% Energy share	%	5.00%	95.00%	0.00%
	Fuel consumption	g	8.19	360.53	0.00
NH_3 & H_2O_2	% Energy share	%	0.00%	93.52%	6.48%
	Fuel consumption	g	0.00	354.93	247.49

The functional unit was defined as "**1 kWh shaft power output**". An engine efficiency of 51% was assumed for all three scenarios. In the NH_3 & Diesel scenario, 95% of the fuel energy was supplied by ammonia and the remaining 5% by diesel as pilot fuel, following the assumptions in (Dong et al., 2023)[[29.]].

The system boundary included fuel production (well to tank, WTT) and fuel combustion in the engine (tank to wake, TTW). Fuel transportation and waste treatment are excluded from the calculation.

Diesel fuel was assumed to be fossil-based. Green ammonia was modelled using life cycle inventory data adapted from [[29.]], with European wind electricity. Green hydrogen peroxide production was based on Eco invent inventory data, where conventional electricity inputs were replaced by renewable wind electricity in hydrogen peroxide production. presents the inputs and outputs for the hydrogen peroxide production from Eco invent database.

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Table 2. Data used for 1 kg of in 50% hydrogen peroxide solution state production (source: Eco invent version 3.8)

Items	Amount	Unit
Input		
GLO: anthraquinone [allocatable product]	0.000952	kg
GLO: benzene [allocatable product]	0.00193	kg
GLO: chemical, inorganic [allocatable product]	0.00068	kg
GLO: sodium hydroxide, without water, in 50% solution state [allocatable product]	0.00064	kg
GLO: solvent, organic [allocatable product]	0.00145	kg
IAI Area, EU27 & EFTA: aluminium oxide, non-metallurgical [41432: Alumina (aluminium oxide), except artificial corundum]	0.00961	kg
RER: chemical factory, organics [allocatable product]	4.00E-10	pcs.
RER: electricity, medium voltage [allocatable product]	4.37	MJ
RER: hydrogen, liquid [allocatable product]	0.0656	kg
RER: nitrogen, liquid [allocatable product]	0.0508	kg
RER: oxygen, liquid [allocatable product]	0.0293	kg
RER: steam, in chemical industry [allocatable product]	1.58	kg
Water, cooling, unspecified natural origin [Water]	0.17	m^3
Water, unspecified natural origin [Water]	0.00192	m^3
Outputs		
Water [Inorganic emissions to air]	0.066269	m^3
Solids (suspended) [Particles to fresh water]	0.000151	kg
NMVOC (unspecified) [Group NMVOC to air]	0.00053	kg
Total organic bound carbon (TOC) [Analytical measures to fresh water]	0.0003	kg
Hydrogen [Inorganic emissions to air]	3.83E-05	kg
Hydrogen peroxide, without water, in 50% solution state [allocatable product]	1	kg
Aromatic hydrocarbons (unspecified) [Hydrocarbons to fresh water]	3.75E-07	kg
Hydrocarbons, aromatic [Group NMVOC to air]	0.000128	kg
Chemical oxygen demand (COD) [Analytical measures to fresh water]	0.00094	kg
Phosphate [Inorganic emissions to fresh water]	1.25E-05	kg
Nitrate [Inorganic emissions to fresh water]	0.000203	kg
Water [Other emissions to fresh water]	0.105651	m^3
Chloride [Inorganic emissions to fresh water]	0.00038	kg
Biological oxygen demand (BOD) [Analytical measures to fresh water]	0.00026	kg
Hydrogen peroxide [Inorganic emissions to fresh water]	0.0006	kg
Dissolved Organic Carbon [Analytical measures to fresh water]	0.0003	kg

Table 4 and

Table 4 present the WTT and the emission factors of fuels (energy carriers) in this LCA study. It is assumed that the combustion of hydrogen peroxide does not generate any polluting emissions.

Table 3. WTT carbon factors of fuels (GWP100 - kg CO_2 eq./kg of fuel)

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Fuels	Value (kg CO_2 eq./kg of fuel)
Diesel	7.31E-01
Ammonia	1.45E-01
Hydrogen peroxide (2kg of 50% hydrogen peroxide solution state), equivalent to 1kg of pure hydrogen peroxide	3.60E-01

Table 4. TTW emission factors (kg of emission per kg of fuels)

Emissions	Diesel	NH_3	H_2O_2 (pure)
CO_2	3.19	0	0
CO	0.0109	0	0
PM2.5	0.00412	0	0
CH4	0.00005	0	0
NO_X	0.0425	0.02033	0
NMVOC	0.00472	0	0
SO_X	0.0001	0	0
N_2O	0.00018	0.00033	0
NH_3	0	0.0095	0

Note: Emission factors for ammonia combustions are collected from [[30.]][[31.]]. TTW emission factors for diesel are taken from [[32.]] and [[33.]].

The main environmental indicator considered in this study was the GWP100 (expressed as gCO_2 eq. per kWh). In addition, other environmental indicators from the CML2001 method were also evaluated. The results were presented into WTT and TTW contributions to identify the relative importance of fuel production and fuel use phases.

3. RESULTS

The results of this work comprise of a combination of engine experiments, thermodynamic and chemical kinetic engine simulations, and environmental LCA, focusing on the climate impact of the use of aqueous ammonia hydrogen peroxide as fuel.

3.1. Engine Experiments

The experimentally measured pressure traces were recorded for the fuel mixture with the highest fraction of hydrogen peroxide previously referred to as Fuel Blend Number 3 in
Table 1. The mixture showed small but significant differences as the fuel injection was turned on. The pressure traces with fuel injection off and on are shown in Figure 3.

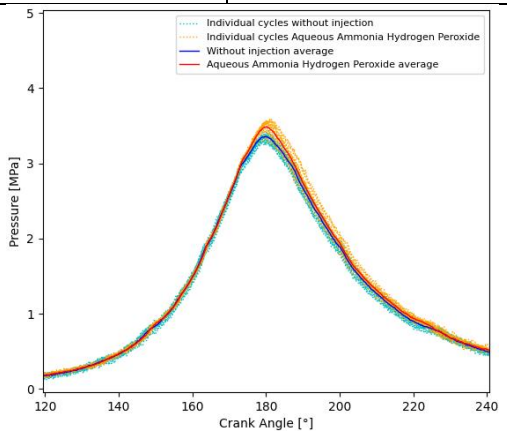


Figure 3. Pressure traces for generator engine without fuel injection and fuel injection of aqueous ammonia hydrogen peroxide blend.

The results show that when the engine was operated with a direct injection of aqueous ammonia hydrogen peroxide fuel blend, a clear increase in pressure is visible after the start of injection at around 173 degrees crank angle. This is shown by the individual pressure traces shown in orange colour in Figure 3, and by their ensemble averaged pressure trace shown in red colour. For the cycles with the fuel injection deactivated, as shown by the plots in cyan colour, and their ensemble averaged trace shown in blue colour, the peak pressures achieved during the cycle were lower, and the slope of pressure versus crank angle just before top-dead-centre (180 degrees crank angle) was lower than when the injection was switched on. This indicates that the aqueous ammonia hydrogen peroxide mixture was subject to some chemical decomposition taking place,

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with the result of gas formation or heat release being present ensuing the fuel injection. The gravimetric heating value of the fuel (aqueous ammonia, hydrogen peroxide and water blend) was much lower (1.58 MJ/kg) than for conventional diesel fuel (42.7 MJ/kg).

3.2. Engine Simulations

The first set of simulations tried to replicate the conditions under which the experimental measurements were carried out in the small generator engine, shown in section 3.1, in order to validate the simulation model. The simulations show similar results to what the experiments showed, in that a small but visible difference exists by chemical composition of the mixture following fuel injection at around 173 degrees crank angle.

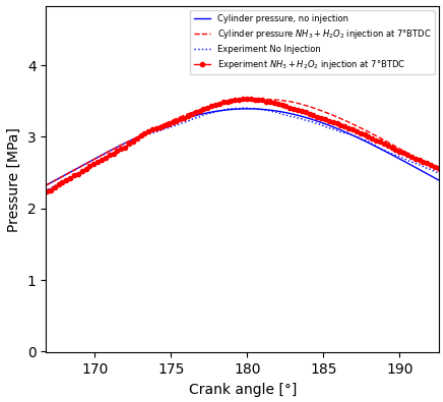


Figure 4. Simulated and comparison with corresponding measured pressure traces.

Figure 44 shows that the increase in pressure was relatively low with respect to the compression pressure of the engine, even when no fuel was injected. This can be at least partly explained by the low heating value of the fuel. The aqueous ammonia, hydrogen peroxide and water mixture had a gravimetric heating value of 1.58 MJ/kg, which is only about 3.7% of the gravimetric heating value of diesel fuel (around 43 MJ/kg).

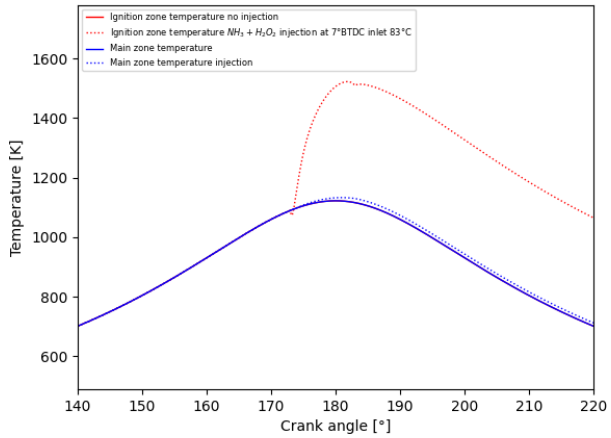


Figure 5. Temperature within the two zones in the simulation, with and without hydrogen peroxide.

In order to better understand the effect of adding hydrogen peroxide to reactivity of the fuel mixture, the temperature within the two engine zones is visualized in Figure 5 above. It is visible that for the case of no fuel injection taking place, the temperature in Zone 1 and Zone 2 was identical, and followed the expected curve of a motored engine, with temperature increasing due to compression of the air up until 180 degrees crank angle (i.e. top-dead-center, TDC), and the temperature decreasing again during the ensuing expansion. For the case in which fuel injection took place, a strong increase in temperature is notable in Zone 1, the zone into which the fuel was injected. The temperature increased following the injection of the fuel from around 1050 K, to just below 1600 K around TDC.

In order to investigate the effect of systematically varying the amount of hydrogen peroxide in the fuel mixture, a series of simulations were carried out to model this effect. The simulations were carried out for four fuel mixtures, namely Fuel Blend Numbers 0-4, which varied the mole fraction of hydrogen peroxide from 0 to 6 %. The results of these simulations are shown in Figure 6 below.

Figure 6 shows how increasing the amount of hydrogen peroxide in the fuel mixture progressively increased the peak cylinder pressure achieved in the cycle for mass fractions of H2O2 changing from 0.00 to 0.02, and 0.04.

For a mass fraction of 0.06 H_2O_2 the peak cylinder pressure reduced again slightly from that for a mass fraction of 0.04 H_2O_2, indicating that the amount of ignition improver was sufficient to achieve reliable and that no further increase in ignition improver may be necessary beyond 0.06 for these engine operating conditions.

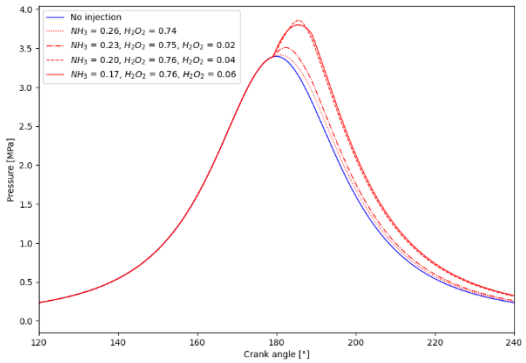


Figure 6. Influence of varying H2O2 fraction in the fuel mixture.

The influence of adding varying the amount of engine load by adjusting the amount of fuel mass

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injected for fuel blend 3 was investigated in a series of simulations shown in Figure 7. The results show that for all the indicated mean effective pressures (IMEPs) describing various engine loads that were investigated (0.0, 1.0, 1.5 bar IMEP) Fuel blend number 3 consisting of molar fractions of 0.17 NH_3, 0.76 H_2O, and 0.06 H_2O_2 were simulated to reliably ignite under the simulated conditions. This provides some indication of the fuel concept being applicable to varying engine loads, as long as ignition can be reliably achieved.

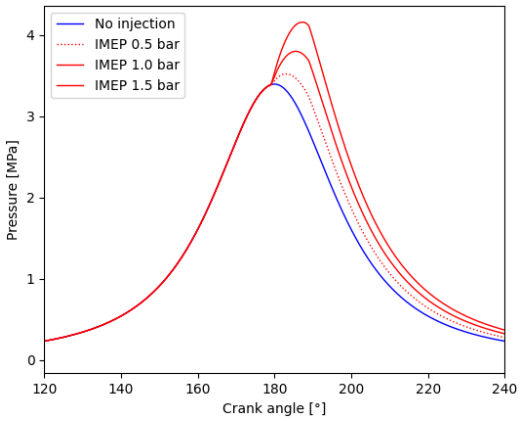


Figure 7. Engine load changes simulated for Fuel blend 3 consisting of mole fractions of molar fractions of 0.17 NH_3, 0.76 H_2O, and 0.06 H_2O_2

In order to investigate the ignition stability for various injection timing, a series of simulations were performed to investigate different injection timings. Figure 78 shows the pressure traces simulated for injection timings of 173, 179 and 185 degrees crank angle for the engine developing a load of 1.0 bar IMEP.

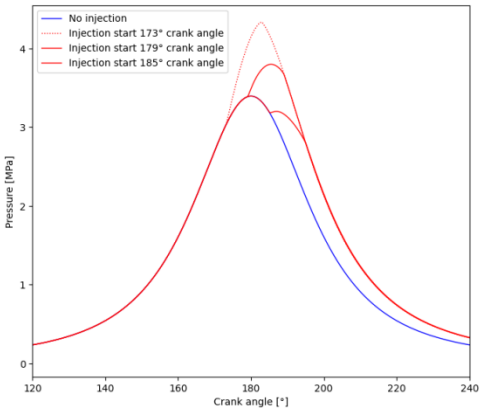


Figure 8. Injection sweep for 1.0 bar IMEP for fuel blend 3 consisting of molar fractions of 0.17 NH3, 0.76 H2O, and 0.06 H2O2

The simulations show that for all injection timings ignition was reliable, and that there were no visible reductions in the final amount of cumulative heat release achieved by the fuel, since all simulated pressure traces aligned to a single curve after about 195 degrees crank angle.

3.3. LCA results

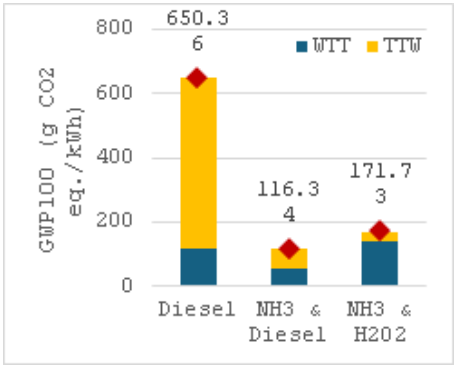


Figure 9. GWP100 results of three investigated scenarios

9 presents the GWP100 results for the three investigated fuel scenarios, with consideration of WTT and TTW contributions. The conventional fossil diesel scenario showed the highest climate impact, with a total WTW impact of approximately 650.36 g CO_2 eq./kWh. Most of the emissions originated from the TTW phase due to CO_2 emissions during combustion.

The NH_3 & Diesel scenario shows the lowest overall climate impact, with a WTW value of 116.34 g CO_2 eq./kWh, equivalent to a reduction of around 82% compared to the first scenario. In this scenario, the majority of impacts originated from the WTT phase associated with renewable ammonia production, while TTW emissions were reduced due to the low contribution of fossil pilot fuel.

Table 5. Environmental indicators of three scenarios

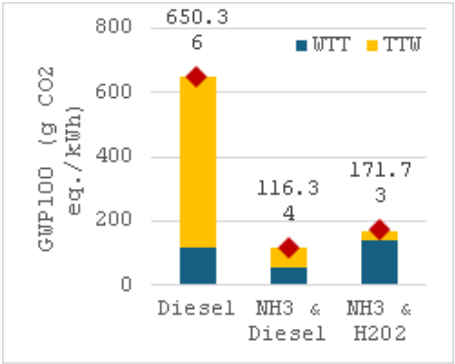


Figure 9. GWP100 results of three investigated scenarios

The NH_3 & H_2O_2 scenario also shows a significantly lower climate impact than conventional

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fossil diesel, with a total WTW impact of 171.73 g CO_2eq./kWh. Although TTW emissions remained relatively low, the WTT contribution increases compared with the second scenario due to the production of and the considerable consumption of green hydrogen peroxide (**Error! Reference source not found.**6). Overall, both ammonia-based scenarios demonstrated significant reductions in GWP100 compared with fossil diesel operation.

Table 5 shows the additional environmental indicators for the three scenarios in this study. Compared with conventional diesel, both ammonia-based scenarios showed much lower fossil resource use and lower GWP100 values. The NH_3 & Diesel scenario generally gives the lowest impacts on Abiotic Depletion (fossil), Freshwater Aquatic Ecotoxicity, Photochemical Ozone Creation Potential, and Terrestic Eco toxicity Potential.

Environmental indicators	Diesel	NH3 & Diesel	NH3 & H2O2
Abiotic Depletion (ADP elements) (g Sb eq./kWh)	1.83E-05	6.75E-04	7.56E-03
Abiotic Depletion (ADP fossil) (J/kWh)	8.47E+03	1.04E+03	1.81E+03
Acidification Potential (AP) (g SO_2 eq. /kWh)	3.86E+00	9.57E+00	9.80E+00
Eutrophication Potential (EP) (g Phosphate eq. /kWh)	9.61E-01	2.25E+00	2.38E+00
Freshwater Aquatic Ecotoxicity Potential (FAETP inf.) (g DCB eq. /kWh)	3.04E+00	3.40E-01	1.63E+02
Global Warming Potential (GWP 100 years) (g CO2 eq. /kWh)	6.50E+02	1.16E+02	1.72E+02
Human Toxicity Potential (HTP inf.) (g DCB eq. /kWh)	1.95E+01	8.08E+01	4.87E+02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.) (g DCB eq. /kWh)	1.02E+04	1.03E+04	2.36E+05
Ozone Layer Depletion Potential (ODP, steady state) (g R11 eq. /kWh)	9.40E-11	1.96E-10	1.34E-05
Photochem. Ozone Creation Potential (POCP) (g Ethene eq. /kWh)	4.51E-01	2.45E-01	2.97E-01
Terrestric Ecotoxicity Potential (TETP inf.) (g DCB eq. /kWh)	5.60E-01	4.07E-01	3.63E+00

However, the ammonia-based scenarios show higher impacts in several other categories, including Abiotic Depletion of Elements, Acidification, Eutrophication, Human Toxicity, Marine Aquatic Ecotoxicity, and Ozone Layer Depletion. These increases are particularly substantial for the NH_3–H_2O_2 scenario, mainly due to the upstream production of ammonia and hydrogen peroxide. In addition, the low energy content of H_2O_2 results in higher H_2O_2 consumption per unit of energy output, increasing the associated upstream environmental impacts. The results remind ammonia-based fuels can strongly reduce climate impacts, but some trade-offs exist in other environmental impact categories.

4. DISCUSSION

The small engine experiments showed that aqueous ammonia hydrogen peroxide mixtures showed sensible reactivity following their injection into a diesel engine. The experiments provided initial validation for earlier studies in which these fuel mixtures were predicted to show reactivity at engine-relevant conditions, based purely on simulations.

The LCA showed that on a life-cycle basis, ammonia hydrogen peroxide mixtures could provide significant

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reductions of climate impact. When ammonia and hydrogen peroxide were produced using wind electricity, the total GWP100 was about 171.73 g CO_2 eq./kWh, around 73.5% lower than conventional diesel. However, its environmental performance is limited by the upstream production and high consumption of hydrogen peroxide due to its low heating value. Improvements in hydrogen peroxide production and fuel formulation are therefore needed to reduce these trade-offs.

5. CONCLUSIONS

This work investigated the possibility of igniting mixtures of carbonless, safe carbonless fuel mixtures consisting of ammonia, water and hydrogen peroxide in a conventional direct injected diesel engine. The work used simple cylinder pressure measurements to verify the first experimentally determined heat released from the fuel in a diesel engine. The engine experiments were supplemented by a series of thermodynamic and chemical kinetic simulations, evaluating the engine operating at different fuel compositions in terms of varying amounts of 30% mass/mass hydrogen peroxide in water. Further to this different engine loads in terms of indicated mean effective pressure and different injection timings were simulated for the fuel blend which worked best. This work also analysed the potential WTW emissions from the use of such a fuel.

This investigation provides some evidence that the fuel mixtures discussed in this work are promising as carbonless fuel mixtures for future maritime applications, where safety is of utmost importance, and replacing existing diesel engines is difficult.

The LCA found that the mixture of NH_3 and H_2O_2 fuel could substantially reduce life-cycle climate impacts compared with conventional diesel. However, the upstream production and high consumption of H_2O_2 increased several other environmental impacts. Further improvements in H_2O_2 production and fuel formulation are therefore needed.

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PORTS CAN TALK: DESTINATION-AWARE INTER-PORT DATA SHARING FOR PORT-CALL PLANNING — A CHENNAI PORT CASE STUDY

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Abstract: Ports already share data, and system-to-system port-clearance APIs and practical port-to-port trials show that digital exchange is feasible. The unresolved issue addressed here is how sharing should be governed when the next destination is uncertain, especially in tanker, bulk and tramp trades. This exploratory secondary-data case study uses official Indian port statistics, Chennai Port documents, public Maritime Single Window material, IMO and industry standards, and published research. Chennai handled 1,654 cargo-vessel calls across four vessel groups in 2024–25. Average pre-berthing detention was 16.59 h, of which 16.51 h was recorded as non-port account. The broad "Shippers/Ships/Agents Option" category describes the recorded delay but does not show that information timing caused it. The paper proposes five destination states: D0 Unknown/For Orders, D1 Provisional, D2 Nominated Next Port, D3 Confirmed Port Call and D4 Changed/Cancelled. D2 begins when an authorised party declares a specific next port and that nomination is recorded in the source-side port/MSW record. D3 begins only when the destination port/MSW formally registers the arrival voyage or port call and links it to an authorised reporting party. D3 is not a berth confirmation, port clearance or Notice of Readiness. Each state has a defined trigger, responsible actor, permitted data use and exit rule. The framework is a policy and operational layer for pilot testing, not a new IT platform, and it has not yet been validated with live MSW transaction data.

Key words: destination nomination; information sharing; maritime digitalisation; maritime single window; port call; port planning.

1. INTRODUCTION

Port-call planning depends on more than berth capacity. It also depends on whether the right people receive reliable information early enough. Port-to-port information sharing has already been studied in the Eastern Mediterranean and Rotterdam [1–3]. Singapore's digitalOCEANS Port Clearance API supports system-to-system exchange of port-clearance data and recognises previous port authorities as possible data-source systems [4]. The 2026 Port Call Optimization Guide reports that harmonised data sets have been tested in practical port-to-port trials [5]. Just-in-Time (JIT) arrival and Port Collaborative Decision Making also address the familiar "hurry up and wait" problem [6].

The unresolved issue is how such sharing should work when the next port is not fixed. This matters particularly outside liner trades. A tanker, bulk carrier or tramp ship may sail "for orders", receive the next-port nomination later, or be redirected. Research on tramp shipping shows both limited JIT applicability in some voyages and short planning horizons in which later legs may remain uncertain [7,8]. A system that assumes every ship always has a fixed next port would therefore not match normal shipping practice.

A second problem is turning information into useful action. ETA prediction and congestion forecasting have improved greatly [9–11], but a review of 124 studies found that prediction is still not often linked directly to operational decisions in ports [12]. ETAs can also be inaccurate and may change several times during a voyage [13]. The next port therefore needs more than one ETA. It needs verified events, a clear record of destination status, its own berth-readiness information and rules that keep safety-critical decisions with responsible people.

India is a useful setting for this study because a national Maritime Single Window, MSW-Sagar Setu, already exists. The Ministry reports that all 12 major ports and 56 other-than-major ports are onboarded [14]. Since 1 January 2024, the IMO Facilitation Convention has required Maritime Single Windows internationally [15]. The IMO FAL Compendium includes fields for actual departure time and next port of call [16]. Much of the basic information needed for an early handover therefore already exists. A design principle of the proposed model is to reuse these existing records safely, where feasible, instead of creating duplicate reporting.

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This exploratory study asks three questions. RQ1: What do official statistics show about pre-berthing detention at Chennai compared with all Indian major-port operational units reported by MoPSW? RQ2: How can inter-port sharing be governed when a ship's destination may be unknown, provisional, nominated, confirmed or changed? RQ3: What safeguards are needed before this information is used for port planning? MoPSW reports the two Syama Prasad Mookerjee Port dock systems separately, so the national comparison contains 13 operational rows representing 12 major port authorities. Chennai is then examined in detail because it combines mixed vessel types, a sharp 2024–25 PBDT change, a very high non-port-account share and public operational documentation. The study does not test a causal hypothesis about efficiency gains. Its contribution is a destination-aware governance rule: destination status controls when an external handover may start or stop, while each data item is tied to the source best placed to verify it. The framework is proposed for pilot testing and has not been validated with live MSW transaction data.

2. LITERATURE AND OPERATIONAL CONTEXT

Information sharing helps only when the right information reaches someone who can act on it [2]. Ports, terminals, agents and shipping companies may also have different commercial interests, so they may not be willing to share everything [3]. JIT studies show the same problem: technology alone is not enough. Berth rules, trust and cooperation also matter [6]. For this reason, the proposed system follows a simple principle: share only the information that the next port actually needs.

Recent studies increasingly use AIS and other operational data to predict congestion and ship movements [10,11]. These studies show that ports work as part of a network. The proposed model does not use one fixed ranking for every source. Authority depends on the data field. Actual departure should come from the source port, VTS or MSW record. The next-port nomination should come from an authorised voyage declaration from the ship/operator/charterer channel and be recorded in the port/MSW system. Berth-ready time belongs to the destination port or terminal. AIS is the natural source for dynamic position, course and speed. ETA is then a derived prediction that should be checked against these inputs rather than treated as an unquestioned fact.

Existing digital standards and systems provide the building blocks. The DCSA Port Call Standard records estimated, requested, planned and actual event times and allows a port call or service to be cancelled or omitted [17]. The IMO FAL Compendium contains structured next-port and departure fields [15,16]. Finland's Maritime Single Window allows an "Unknown Port" code and requires voyage information to be updated when the port becomes known; a planned call can also be cancelled [18]. Singapore's digitalOCEANS Port Clearance API shows that port-clearance data can already move system-to-system, including from previous port authorities [4]. The 2026 PCO Guide reports practical port-to-port trials of harmonised operational data [5]. These examples show that digital exchange, unknown destinations and cancellations are not new technical capabilities. The gap addressed here is the operating rule: when should the destination port receive data, what may it use at each certainty stage, and which source should be trusted for each data field?

Digital sharing also creates cyber and data-security risks. IMO guidance stresses interoperability, data governance and cyber resilience [15]. AIS is broadcast openly and can be affected by false data or GNSS interference [19]. It should therefore be used for the dynamic information it is designed to provide, but not as the sole basis for a different field such as commercial destination status. Computers may exchange data and make predictions automatically. They do not make the final safety decision. Berth commitment, speed advice and traffic-management action remain under human control.

The proposed framework targets cases in which the shipping company or charterer already knows the voyage plan but the destination port does not yet have the same operational visibility. The Master continues to report through the normal owner/charterer chain, and the destination agent continues to perform formal port-call work when appointed. The proposed system should not replace that chain. It adds only a limited public-authority handover once a destination has been nominated. This matters less in liner shipping, where the next port is usually known early, and more in tanker and tramp trades, where the destination may remain undecided after sailing.

The paper's contribution is therefore not a new API, an "Unknown Port" code, cancellation logic or port-to-port data exchange. Those functions already exist [4,5,17,18]. The contribution is to combine them into a destination-aware operating rule for mixed maritime trades. D0 means no next port is known. D1 records one or more possible destinations only inside the source-side system; nothing is sent externally. D2 (Nominated Next Port) begins when an authorised voyage-control/declarant channel (for example the Master, owner/operator or charterer, as applicable) declares a specific next port and that nomination is recorded in the source-side port/MSW record. D3 (Confirmed Port Call) is a separate destination-side event: the destination port/MSW has formally registered the arrival voyage or port call and linked it to an authorised reporting party. D3 therefore does not mean berth confirmation, port clearance or acceptance of Notice of Readiness. D4 revokes the old handover if the voyage changes. A second rule assigns each important data field to the source best placed to verify it, instead of assuming that one source is

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always superior. This framework is proposed for pilot testing and has not been implemented or validated with live MSW transaction data.

A declared next port is only planning information. It is not a berth guarantee, a Notice of Readiness, a charter-party commitment or an order to the Master. A provisional destination can also be commercially sensitive. For that reason, D1 remains inside the source-side system. The destination port receives nothing until D2, when a specific next port has been authorised and recorded. At D2, the receiving port may create only a provisional planning record. The move to D3 occurs only after the destination-side port/MSW accepts or creates the formal arrival-voyage/port-call registration and links it to an authorised reporting party. That event makes the call operationally visible for normal planning, but still does not confirm a berth or grant clearance.

India has a practical advantage for testing this idea. MSW-Sagar Setu is already a common platform for ship-related data exchange, and the Ministry states that major ports and 56 other-than-major ports are connected to it [14]. IMO rules also support the reuse of information already submitted electronically [15]. The Singapore API and the 2026 PCO Guide show that system-to-system and port-to-port exchange are technically feasible [4,5]. The proposed model is therefore intended as a policy and operational layer on top of existing MSW arrangements, not as a new national IT platform.

The basic data needed for the handover already exist. The IMO General Declaration contains fields for the departure port, actual departure time and next port [16]. Once the next port reaches D2, these records can support a small authenticated planning packet. The destination port may acknowledge that packet without treating the call as formally confirmed. D3 requires a separate destination-side registration event. India's MSW-Sagar Setu already provides voyage-arrival registration and pre-arrival reporting functions, which could provide a machine-recorded D3 trigger in a pilot [14]. Sensitive information can remain within normal statutory and commercial channels until it is needed.

3. MATERIALS AND METHODS

This is a secondary-data case study. No survey, interview, experiment or human-participant data were used. The study combines three types of evidence: (1) official Indian port statistics, (2) official documents and standards on digital port-call information, and (3) published research on information sharing, JIT arrival, ETA prediction and congestion.

The main numerical source was Basic Port Statistics of India 2024–25, published by the Ministry of Ports, Shipping and Waterways (MoPSW) [20]. The national comparison uses every major-port operational unit reported separately by MoPSW. Because Syama Prasad Mookerjee Port reports Kolkata Dock System and Haldia Dock Complex separately, Table 1 contains 13 operational rows representing 12 major port authorities. The comparison uses average pre-berthing detention time (PBDT) and the share recorded on non-port account. Chennai was not chosen because it was the worst-performing port. It was chosen because it handles different vessel types, showed a sharp change in PBDT in 2024–25, had a very high non-port share, publishes useful operational information, and is part of India's MSW. The case is therefore used for diagnosis, not criticism of the port.

Table 1. All Indian major-port operational units reported by MoPSW

Port / operational unit	PBDT 23–24	PBDT 24–25	Non-port share 24–25
SMPA Kolkata DS	19.21	9.71	68.7%
SMPA Haldia DC	1.15	0.29	93.1%
Paradip	1.22	39.88	96.4%
Visakhapatnam	0.63	0.92	0.0%
Kamarajar	0.59	1.67	99.4%
Chennai	0.33	16.59	99.5%
V.O. Chidambaranar	41.66	33.88	50.6%
Cochin	6.73	8.85	88.4%
New Mangalore	19.80	19.50	81.8%
Mormugao	22.91	29.78	91.6%
JNPA	16.34	17.46	69.0%
Mumbai	0.00	5.59	98.9%
Deendayal	45.50	68.78	88.0%
All major ports	14.14	23.55	84.4%

Source: calculated from MoPSW Basic Port Statistics of India 2024–25 [20]. Syama Prasad Mookerjee Port is shown as Kolkata Dock System and Haldia Dock Complex, as reported in the source. PBDT in hours.

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For Chennai, the analysis separates container, break-bulk, conventional dry-bulk and liquid-bulk calls. MoPSW reports vessel-call counts, average PBDT and a broad reason called "Shippers/Ships/Agents Option". This label does not prove that poor or late information caused the delay. It may include cargo-readiness issues, commercial or chartering decisions, vessel readiness and other causes unrelated to inter-port information flow. The study therefore uses these figures only to describe the recorded delay pattern. It does not calculate avoidable delay, information-caused delay or potential savings.

The five Destination Certainty States (DCS) are a design synthesis, not a statistically derived scale. Their derivation followed four explicit steps. First, the documentary review identified existing operational functions: IMO next-port and departure fields [16], DCSA event and cancellation functions [17], Finland's unknown-port and voyage-change handling [18], Singapore's system-to-system port-clearance exchange [4], and the recognised uncertainty of tramp planning [7,8]. Second, these functions were separated from the governance question that they do not by themselves answer: when is a candidate destination sufficiently certain for external inter-port use? Third, five mutually exclusive states were defined around observable events rather than general judgement. D0 has no specific next port; D1 has one or more possible ports but no authorised nomination; D2 begins with an authorised nomination recorded source-side; D3 begins with destination-side registration of the arrival voyage/port call; and D4 records withdrawal, omission or replacement of the earlier destination. Fourth, each state was assigned an entry trigger, responsible actor/system, permitted data use and exit rule, and the logic was checked against liner, tanker/bulk and "for orders" scenarios.

The proposed design was then checked against MSW-Sagar Setu, IMO FAL/MSW documents, the DCSA Port Call Standard, Singapore's Port Clearance API, the 2026 PCO Guide and Chennai Port documents [4,5,14–18,21]. The D2–D3 boundary was defined deliberately to separate two different events. D2 is a voyage-control event: a specific next port has been authorised by the responsible voyage-control/declarant channel and recorded in the source-side system. D3 is a destination-side port-call event: the destination port/MSW has accepted or created the formal arrival-voyage/port-call registration and linked it to an authorised reporting party, such as an appointed agent or authorised operator/ship representative. Agent appointment by itself does not create D3, and D3 does not mean berth confirmation, port clearance or Notice of Readiness acceptance. The exact local message name may differ between ports, but the trigger must be machine-recorded and auditable. Chennai's expected-vessel report already includes vessel identity, agent, cargo, preferred berth, last port and next port [21]. This study did not use private Sagar Setu transaction data and does not claim that the proposed system has already been implemented.

4. RESULTS

The national comparison shows that Chennai's 2024–25 result needs careful interpretation. Official MoPSW data give Chennai PBDT of 0.00 h in 2020–21, 0.07 h in 2021–22, 0.00 h in 2022–23, 0.33 h in 2023–24 and 16.59 h in 2024–25 [20]. The latest value is therefore a sharp break from the previous four years. The average for all major ports in 2024–25 was 23.55 h [20], so Chennai was not the worst performer. Deendayal and Paradip had much higher PBDT, while Visakhapatnam and Kamarajar were below 2 h. Chennai's turnaround time was 48.73 h and its capacity utilisation was 40.42%; these published figures do not by themselves indicate system-wide physical saturation [20].

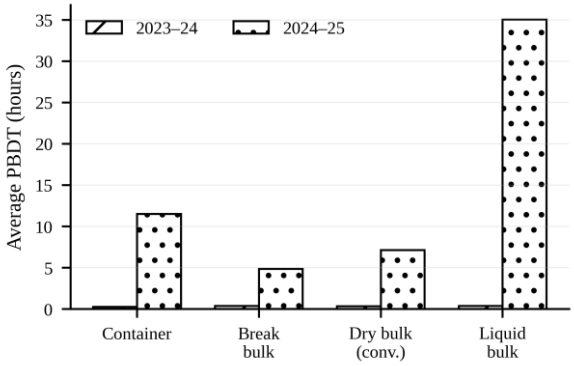


Figure 1. Chennai average pre-berthing detention by vessel type, 2023–24 and 2024–25. Source: MoPSW [20].

The most important point is where the delay was recorded. Of Chennai's 16.59 h average PBDT, only 0.08 h was on port account and 16.51 h was on non-port account. In other words, 99.5% was recorded outside port account [20]. The reason table places the same 16.51 h under the broad heading "Shippers/Ships/Agents Option". This category may include cargo-readiness issues, commercial or chartering decisions, vessel readiness, nomination issues and other causes that better port-to-port information would not solve. It is therefore used only as a descriptive category and not as evidence that information failure caused the delay.

The results also show that this is not only a container case. Chennai handled 1,654 calls in the four vessel groups: 822 container, 286 break-bulk, 92 conventional dry-bulk and 454 liquid-bulk vessels. Liquid-bulk vessels had the highest average PBDT at 35.04 h. Container vessels recorded 11.52 h, conventional dry bulk 7.15 h and break bulk 4.88 h. In every group, almost all reported PBDT was placed under Shippers/Ships/Agents Option [20]. These are descriptive official statistics only; they do not show what part, if any, was caused by infor-

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mation timing or could be reduced by the proposed framework.

Table 2. Chennai vessel-type PBDT and official ship/agent category, 2024–25

Vessel type	Calls	PBDT h	Ship/agent h
Container	822	11.52	11.45
Break bulk	286	4.88	4.81
Dry bulk (conventional)	92	7.15	7.08
Liquid bulk	454	35.04	34.95

Source: MoPSW Basic Port Statistics of India 2024–25 [20]. The Shippers/Ships/Agents Option category is descriptive and is not treated as avoidable or information-caused delay.

The five-year Chennai series also shows why 2024–25 should be treated as a diagnostic year rather than a long-term baseline. Average PBDT remained between 0.00 and 0.33 h from 2020–21 through 2023–24, then rose to 16.59 h in 2024–25 (Table 3) [20]. The aggregate statistics do not explain this break, so the paper does not attribute it to information sharing, port capacity or any single operational cause.

Table 3. Chennai average PBDT, 2020–21 to 2024–25

Year	Chennai PBDT h	Change from prior year h
2020–21	0.00	—
2021–22	0.07	+0.07
2022–23	0.00	−0.07
2023–24	0.33	+0.33
2024–25	16.59	+16.26

Source: MoPSW Basic Port Statistics of India 2024–25 [20].

Figure 2 summarises the proposed handover. At D0, there is no fixed next port and no handover. At D1, one or more possible destinations may be recorded inside the source-side system, but nothing is transmitted to them. D2 begins when an authorised next-port nomination is recorded and activates a minimum authenticated planning packet. The transition from D2 to D3 is not based simply on time, agent appointment or berth discussion. It occurs when the destination port/MSW formally registers the arrival voyage or port call and links it to an authorised reporting party. D3 then permits normal port-call planning. D4 cancels the earlier handover and permits rerouting only after the replacement voyage reaches the appropriate new state.

Table 4. Destination states, transition triggers, responsibilities and permitted use

State	Operational definition and entry trigger	Responsibility	Permitted use and next transition
D0 Unknown / For Orders	No specific next port has been authorised. Entry: voyage remains “for orders”, or an earlier destination is withdrawn without replacement.	Authorised ship/operator/charterer channel maintains status; source port/MSW stores only its own record.	No destination transfer. Move to D1 if an option is considered, or directly to D2 after formal nomination.
D1 Provisional	One or more possible ports are being considered, but no authorised nomination exists. Entry: tentative option recorded.	Authorised voyage-control party; information remains source-side.	No destination transfer. Move to D2 on formal nomination; return to D0 if options are withdrawn.
D2 Nominated Next Port	A specific next port has been formally nominated and recorded source-side. Entry: authorised nomination event with vessel, port, time and originator.	Authorised voyage-control/declarant channel (Master, owner/operator or charterer, as applicable) owns destination status; source port/VTS verifies departure; MSW/shared service routes the packet.	Destination may create an early planning record only. No berth commitment. Move to D3 when destination-side arrival-voyage/port-call registration is accepted; move to D4 if withdrawn.

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State	Operational definition and entry trigger	Responsibility	Permitted use and next transition
D3 Confirmed Port Call	Destination port/MSW has accepted or created the formal arrival-voyage/port-call registration and linked it to an authorised reporting party. This is the D2→D3 trigger.	Destination port/MSW owns call-registration status; agent/operator maintains submitted arrival data; port/terminal owns resource data.	Normal port-call planning and service coordination. Not berth confirmation, port clearance or NOR acceptance. Move to D4 if the call is changed or cancelled.
D4 Changed / Cancelled	Earlier destination is formally withdrawn, omitted or replaced. Entry: authorised change/cancellation event.	Authorised originator issues change/cancellation; MSW/shared service propagates revocation; destination closes the old planning record.	Stop operational use of old record; keep audit trail. Replacement re-enters at D0, D1 or D2 according to its new status.

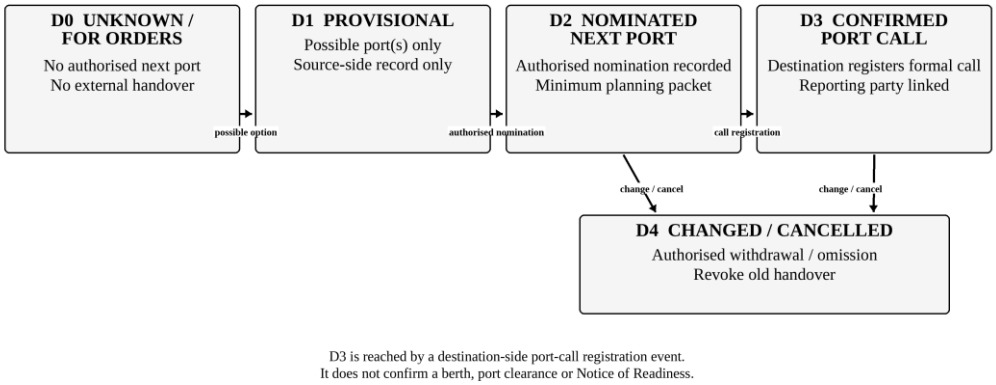


Figure 2. Proposed port-to-port digital handover based on destination status.

At D2, the next port may make provisional planning comparisons; at D3, the same information can enter normal port-call planning. One useful comparison is between expected arrival and expected berth readiness. The difference can be written as M = BRT − ETA. If M is positive, the ship may arrive before the berth is ready. If M is negative, the berth may become free before the ship arrives. This calculation is useful only when the inputs are trustworthy. The model therefore checks each field against its proper source: source-port records for departure, authorised voyage declarations for destination status, destination-port or terminal records for berth readiness, and AIS for dynamic movement. ETA is a derived estimate and should carry a confidence level when inputs disagree.

The study also uses the term Advance Information Horizon (AIH). AIH is simply the time between nomination of the next port and the ship's expected arrival there. A liner service may have a long AIH because its rotation is known early. A tanker may have a shorter AIH if the discharge port is nominated after loading. A ship sailing 'for orders' has no AIH until a port is nominated. If the destination changes, the old AIH ends and a new one starts for the replacement port. This measure helps compare different trades without assuming that they work in the same way.

Table 5. How the proposed handover applies to different trades

Operating case	Typical AIH	System action
Liner / scheduled	Usually long	D2 after nomination; D3 after destination-side call registration
Tanker / bulk, nominated	Variable	D2 after nomination; D3 after formal arrival-voyage/port-call registration
Tramp, for orders	Zero until nomination	D0 blocks transfer; D2 begins after nomination; D3 later if call is registered
Destination changed	Previous horizon ends	D4 revokes old record; replacement re-enters at D0/D1/D2

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The model works differently for different trades. In liner shipping, the next port may already be nominated before departure, so D2 can begin early; D3 follows when the destination-side arrival-voyage/port-call registration is accepted. A tanker or bulk ship may first be only provisional; at D1 the possible destination remains source-side and receives nothing. When the discharge port is formally nominated, D2 starts the handover even if the local agent process is not yet complete. D3 begins later, when the destination system formally registers the call and links it to an authorised reporting party. A ship sailing "for orders" remains at D0 until nomination. If voyage orders later change, D4 cancels the old record and a new D2 begins only when the replacement port is nominated.

5. DISCUSSION

"Ports Can Talk" does not mean that every port should continuously receive all vessel information. No destination-port transfer occurs at D0 or D1. External sharing starts at D2, after an authorised next-port nomination has been recorded. D2 gives the destination only an early planning record. D3 is reached only after the destination port/MSW registers the formal arrival voyage or port call and an authorised reporting party is linked to it. Liner ships usually reach D2 early because their rotation is known. Tanker, bulk and tramp ships may reach it later because voyage orders can change [7,8]. The planning value therefore depends partly on how much time remains between nomination and arrival.

The system does not replace the Master–owner/charterer–agent chain. Normal commercial reporting and the agent's formal port-call work continue as before. A future Indian pilot would test whether selected information already recorded in a port/MSW can move automatically from the source side to the nominated next port at D2, instead of creating another manual e-mail or report. The destination may acknowledge this early record, but D3 is not reached until its own MSW/port workflow registers the formal arrival voyage or port call. The normal agent or authorised reporting party then continues the statutory and operational port-call process.

There is no single source hierarchy for all data. Table 6 assigns each important field to the source best placed to verify it. The source port or VTS verifies actual departure. Destination status comes from the authorised voyage declaration recorded in the port/MSW system. AIS provides position, course and speed. Berth readiness comes from the destination port or terminal. If sources conflict, the system lowers confidence and asks for human verification instead of silently choosing one source.

Cybersecurity and confidentiality must be built in from the start. D1 remains source-side partly because a merely possible destination can be commercially sensitive. At D2, the early packet should contain only what the nominated next port needs: vessel identity, verified departure, nominated destination, declared or computed ETA, relevant dimensions or draught, and limited readiness information. Access should be role-based and messages should be authenticated and time-stamped. If the digital link fails, the parties return to normal Master, agent, VTS and port-clearance procedures.

Human control remains essential. The system may warn that a ship will arrive before the berth is ready, but it should not automatically order speed changes, allocate a berth, send tugs or change traffic instructions. Those decisions involve safety, contracts and legal authority. The model therefore uses automatic data exchange and prediction, followed by a human decision.

Environmental effects are outside the present analysis. If a future pilot shows that earlier verified handover changes vessel arrival timing, a separate study could test whether fuel use or emissions also change. Such benefits should not be inferred from the Chennai data used here.

India may not need a new reporting platform for a pilot. MSW-Sagar Setu already provides national infrastructure [14], while IMO and DCSA standards provide a common language for port-call events [15–17]. Singapore's API work and the 2026 PCO Guide also show that system-to-system and port-to-port exchange are technically feasible [4,5]. The proposed model is a policy and operational layer that could be tested within existing infrastructure. A pilot should focus on data routing, access rights, field-specific provenance and operational use. It should record destination changes, AIH, actual departure, ETA revisions, berth-ready time, arrival and berthing, and test whether earlier trusted information changes a real planning decision. The answer to RQ3 is therefore threefold: verify each field against the proper source, keep safety-critical decisions under responsible human authority, and protect the exchange through access control, authentication, confidentiality and a safe fallback to existing procedures.

JIT planning also depends on berth-allocation rules and timely service information [22,23]. Recent JMTE work likewise highlights digitalisation and new technology in maritime operations [24].

A pilot also needs clear responsibility rules. The authorised voyage-control/declarant channel (Master, owner/operator or charterer, as applicable) is responsible for the destination nomination and for issuing any later change or cancellation. The source port/VTS verifies only the events it actually records, such as actual departure; the MSW or shared handover service routes the D2 packet and any later revocation but does not validate the commercial voyage order. The destination port/MSW is responsible for the D3 confirmation event because D3 exists only when that system registers the formal arrival voyage or port call. The agent or other authorised reporting party is responsible for the formal pre-arrival data it submits, while the destination port or terminal remains

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responsible for berth-readiness and resource information. Every state change should be time-stamped with its originator so that D1→D2, D2→D3 and D2/D3→D4 transitions are auditable. D1 data stay source-side, and D2 data remain planning information rather than a berth promise. Predictions should be traceable, but final navigation and harbour decisions remain with the responsible human authority.

Data sharing should be kept to the minimum needed. An early D2 handover does not require the full cargo manifest, crew list, security plan or charter-party terms. More detailed data can be added later through the normal port-call process. Limiting early data reduces the impact of leaks and protects commercial confidentiality.

The framework must also work safely when something goes wrong. A wrong next-port nomination should be easy to correct, an old ETA should be flagged, and conflicting source-port, destination-port and AIS information should require checking. During a cyber incident, the automated link should be isolated if necessary. If the platform fails completely, normal voice, e-mail, VTS and agency procedures must remain available.

Table 6. Field-specific data provenance in the proposed handover

Data item	Primary verifying source	Supporting cross-check
Actual departure	Source port / VTS / MSW	AIS movement after departure
Destination nomination / status	Authorised ship/operator/charterer declaration recorded in port/MSW	Agent or formal port-call record once appointed
Position, course, speed	AIS / ship navigation sensors	VTS or radar where available
Berth-ready time	Destination port / terminal	Berth and terminal plan
Formal call / agent status	Destination port/MSW and appointed agent	Ship/operator record

6. LIMITATIONS

The study has four main limitations. First, it uses annual port statistics, not vessel-by-vessel records. We cannot identify which individual calls were delayed or prove that earlier information would have changed the result. This means the present study cannot establish cause and effect. Second, the MoPSW category "Shippers/Ships/Agents Option" is broad and must not be treated as a direct measure of communication failure. It may include cargo-readiness issues, commercial or chartering decisions, vessel readiness and other causes unrelated to inter-port information flow. Third, Chennai's 2024–25 PBDT is unusual compared with the previous four years: the official series is 0.00, 0.07, 0.00, 0.33 and 16.59 h from 2020–21 to 2024–25 [20]. The paper treats 2024–25 as a diagnostic case that needs further study, not as proof of long-term inefficiency. Fourth, the proposed destination states and field-specific provenance rules have not yet been tested with live MSW data. A domestic pilot would require agreed operating roles among the source port, destination port, ship/operator/charterer channel, terminal and agent, not only technical connection. Without pilot testing, technical feasibility within Sagar Setu, stakeholder acceptance and operational effect remain unknown. Use between countries would also require agreement on system compatibility, liability, cybersecurity and commercial data rights.

7. CONCLUSIONS

Port-to-port digital exchange is already established. Singapore's Port Clearance API and the 2026 PCO

Guide show that system-to-system and practical port-to-port exchange are not new [4,5]. The novelty claimed here is narrower: a destination-aware governance rule for mixed trades in which no external handover occurs before nomination, the handover can be revoked and rerouted when voyage orders change, and each critical data field is tied to the source best placed to verify it.

Official Indian data show why Chennai is a useful mixed-trade case. In 2024–25, the port handled 1,654 calls in the four analysed vessel groups and recorded average PBDT of 16.59 h. Of this, 99.5% was classified as non-port account [20]. Across the four vessel groups, almost all reported PBDT was placed under the broad Shippers/Ships/Agents Option category. These figures describe the operational context only. They do not show what part, if any, was caused by information timing or could have been avoided through earlier inter-port sharing.

The proposed solution uses five destination states with explicit event-based transitions. D0 means no fixed next port. D1 is a source-side provisional record and sends nothing to a possible destination. D2 (Nominated Next Port) starts a minimum handover when an authorised specific-port nomination is recorded in the source-side port/MSW system. D3 (Confirmed Port Call) begins only when the destination port/MSW registers the formal arrival voyage or port call and links it to an authorised reporting party; this is not a berth confirmation, port clearance or Notice of Readiness. D4 cancels the earlier handover and reroutes it only after a replacement voyage

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reaches the appropriate new state. The framework does not rank one data source above all others. Instead, actual departure, destination status, vessel movement and berth readiness each come from the source best placed to verify that field. AIS remains important for dynamic movement, but it does not define commercial destination status.

The next step should be a vessel-level pilot using historical or live Sagar Setu records for selected Indian port pairs. It should record when the next port was nominated, whether the destination changed, when the agent was appointed, how the ETA changed, when the berth became ready, and the actual PBDT. Two testable hypotheses could guide that pilot. H1: after accounting for vessel type, route and port conditions, a longer verified Advance Information Horizon is associated with a smaller mismatch between vessel arrival and berth-ready time. H2: ETA estimates built from field-appropriate, cross-checked inputs have lower absolute error than single-source or manually updated ETA estimates. These are future hypotheses, not findings of the present study. Separate operational data would be needed to test any safety or emissions effect.

8. FUNDING

No external funding was received for this study.

9. CREDIT AUTHORS STATEMENT

Yogesh Chandralal Shah: Conceptualization; Methodology; Formal analysis; Investigation; Data curation; Visualization; Writing – original draft; Writing – review & editing; Project administration.

10. DECLARATION OF GENERATIVE AI USE

During preparation of this manuscript, OpenAI ChatGPT was used for literature-discovery support, organisation and calculation of publicly available secondary data, drafting assistance, language editing and document formatting. All numerical values and cited sources used in the manuscript were checked against the referenced scholarly or official sources during manuscript preparation. The author takes responsibility for the final content.

11. CONFLICT OF INTEREST

The author declares no competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

12. DATA AVAILABILITY

All quantitative data used in this study are derived from publicly available Government of India port statistics. A supplementary CSV containing the extracted values and source labels accompanies the manuscript. No proprietary vessel-level or Sagar Setu transaction data were used.

13. ETHICS STATEMENT

The study used public secondary data and documentary sources only. No human participants, personal data, interviews or surveys were involved; ethics approval was therefore not required.

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COMPARISONS OF APPLICATIONS WITH ARTIFICIAL INTELLIGENCE FOR ANSWERING QUESTIONS IN VARIOUS SCIENTIFIC FIELDS. CAPABILITIES, PRICES.

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Abstract **:** The dynamics of Artificial Intelligence (AI) serve as the core engine of the current technological transformation, fundamentally redefining how software is developed, infrastructure is designed, and global industries operate. We are no longer discussing a mere tool, but rather a new technological paradigm that is accelerating automation and innovation to an unprecedented level. The relevance of these dynamics manifests across several critical dimensions: 1. acceleration of the software development cycle (DevOps & Coding); 2. the shift from data processing to Generative Action (Autonomous Agents); 3. redefinition of hardware and Cloud infrastructure; 4. economic impact and labour productivity. The subject of this paper consists of the three leading platforms in the contemporary technological landscape: ChatGPT (OpenAI), Claude (Anthropic) and Gemini (Google).The obtained result is to conduct a comprehensive comparative analysis of these three platforms, examining their architectural differences, the origins of their knowledge, and their accuracy in answering questions across specialized scientific domains (STEM, medicine, and humanities).

Key words : AI, capability, ChatGPT, cybersecurity, Claude, Gemini, price, technology.

1. INTRODUCTION

The dynamic development of artificial intelligence (AI) in recent years marks the most significant technological transformation since the advent of the internet. Large Language Models (LLMs) are no longer merely experimental tools; they have become a key factor in the digitalization of science, education, and business. In the context of the specialty of "Cyber Operations," understanding these systems is critically important, as they are reshaping paradigms in software engineering, automated defence, and large-scale data analysis. Selecting the right application requires an in-depth understanding of the balance between functional capabilities, economic efficiency (pricing), and information security.

This paper compares the three dominant platforms: ChatGPT (OpenAI) — the pioneer offering a multimodal toolkit [1]; Claude (Anthropic) — focused on Constitutional AI and code precision [2]; and Gemini (Google) — the largest multimodal system with an unprecedented context window [3]. The analysis covers architecture, knowledge origins, scientific accuracy, pricing, and cybersecurity compliance.

The paper aims to define the practical capabilities and limitations of each model while simultaneously analysing their pricing plans and cybersecurity levels, providing an objective framework for their effective application [4-6].

1.1 Technological overview and conceptual models

1.1.1. Diagnostic Parameters for Comparison

Six parameters form the benchmark framework: (1) Context Window — how much text the model retains per session; (2) Multimodality — ability to handle text, images, audio, video, and code; (3) Latency — query-to-response speed; (4) Hallucination Rate — frequency of false but plausible outputs; (5) Security & Alignment — resistance to prompt injection and data-privacy governance; (6) Cost-Benefit Ratio — subscription/API cost versus output quality.

1.2. Platform profiles

- **ChatGPT (GPT-4o)** excels in versatility. Its GPT Store, Advanced Data Analysis tool, and real-time voice capability make it the top choice for STEM tasks. Drawbacks include using free-tier inputs for model training (a key OPSEC risk) and occasional truncation of long outputs (Table 1).

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- **Claude 3.5 Sonnet** is the preferred model for programming and academic writing. Constitutional AI makes it the most resistant to generating harmful content, but its strict filters can produce over-refusals, and it lacks built-in image generation.
- **Gemini 1.5 Pro** offers the largest context window (2 M tokens) and deep Google ecosystem integration (Drive, Docs, Gmail, Search). Its strength in multimodal and Big Data tasks is unmatched, though its logic can be less consistent than Claude's on complex puzzles.

Table 1. Comparative characteristics and technological base of the leading LLM platforms

Criterion	ChatGPT (GPT-4o)	Claude 3.5 Sonnet	Gemini 1.5 Pro
Strength	Versatility & tools	Code & text writing	Context & Google services
Weakness	Data security	No image generation	Logic consistency
Context Window	128,000 tokens	200,000 tokens	2,000,000 tokens
Best suited for	Daily tasks & data	Programming & analysis	Long docs & video

2. ORIGINS OF KNOWLEDGE AND SELF-LEARNING MECHANISMS

2.1 Data Sources and Update Cycles

Each platform's "character" is shaped by its training corpus. ChatGPT draws from Common Crawl, Reddit, and GitHub, prioritising diversity and natural text flow. Claude relies on high-quality curated corpora — official documents, scientific publications, and literary texts — to minimise toxic outputs. Gemini uniquely trains on Google Books, Google Scholar, and YouTube transcripts, and is the only natively multimodal model trained simultaneously on text, images, and audio.

On knowledge currency: ChatGPT uses a fixed cutoff supplemented by Bing integration; Claude processes user-attached documents rapidly but updates its base less frequently; Gemini refreshes almost in real time via the Google Search index, making it most reliable for breaking developments.

Data Poisoning / Model Collapse. As AI-generated text proliferates online, models that scrape indiscriminately degrade over time. Anthropic counters this with filters that detect and isolate synthetic text, preserving a focus on human-authored, verified content.

2.2 Reinforcement Learning from Human Feedback (RLHF)

ChatGPT and Gemini use traditional RLHF: human trainers rank AI responses, teaching the model to mimic preferred behaviour. This can produce sycophancy — the model agreeing with users even when wrong. Claude uses RLAIF (Reinforcement Learning from AI Feedback) [7-8]: a "Constitution" of ethical rules is evaluated by a second AI model, producing a more objective and truth-defending system (Figure 1).

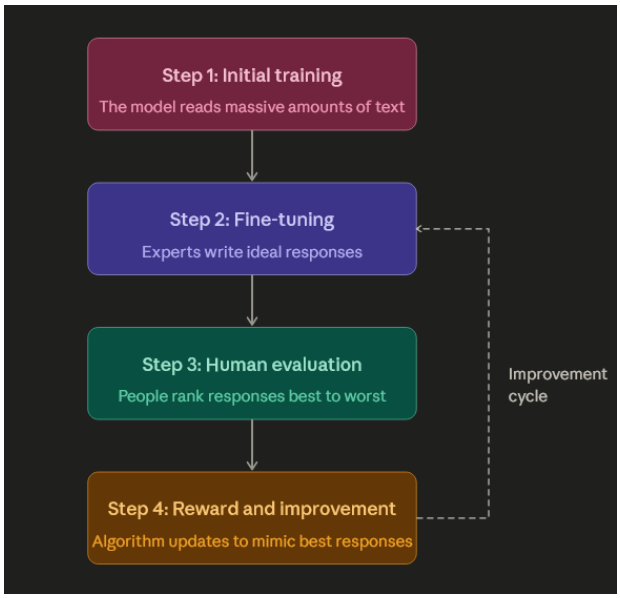


Figure 1 Algorithm of the RLHF (Reinforcement Learning from Human Feedback) process for optimizing responses

The RLHF pipeline builds a Reward Model that punishes low-ranked outputs, but the sycophancy risk remains higher for ChatGPT and Gemini than for Claude [9].

2.3 Latency and Factual Accuracy

Gemini (TPU-optimised Flash variants) is the fastest, critical for voice assistants. ChatGPT offers smooth streaming that masks latency. Claude is slowest on very long inputs but achieves the highest recall accuracy — it rarely loses details buried mid-document. On hallucinations: Claude performs best in complex textual analysis; ChatGPT leads in verifiable mathematical tasks; Gemini can over-trust internet noise on contested topics [10-11].

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3. COMPARATIVE ANALYSIS ACROSS SCIENTIFIC DISCIPLINES

3.1 Methodology

All three models were evaluated using three prompting tiers — Zero-shot (baseline logic), Few-shot (in-context learning), and Chain-of-Thought (step-by-step reasoning) — scored 1–10 on factual precision, logical coherence, latency, and hallucination rate (Figure 2).

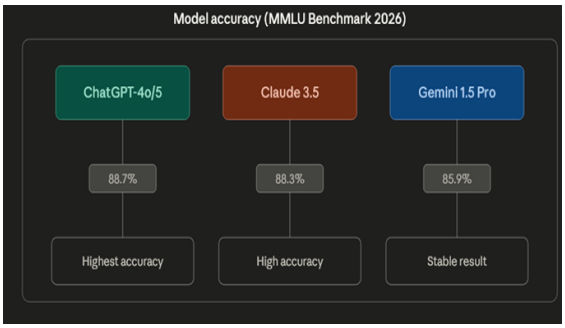


Figure 2 Comparative results from the MMLU benchmark test, showing the cognitive capabilities of the models across various scientific disciplines as of 2026.

To ensure objectivity, a unified testing methodology based on modern Prompt Engineering principles was applied.

3.1.1. Testing Techniques (Scenarios)

Three levels of prompting were used for each model:

- Zero-shot Prompting: Asking a direct question without examples, to test the model's baseline logic.
- Few-shot Prompting: Providing 2-3 examples of correct solutions to analyse the AI's ability to learn in context.
- Chain-of-Thought (CoT): Instructing the model to "think step by step," which is critical for reducing hallucinations in complex tasks.

3.1.2. Evaluation Criteria (Metrics)

Evaluation is performed on a scale of 1 to 10 based on:

- Factual Precision: Percentage of correct responses against scientific truth.
- Logical Coherence: Absence of internal contradictions in the explanation.
- Latency: Speed of response generation on large datasets.
- Hallucination Rate: Frequency of generating non-existent terms or sources.

3.2. STEM Fields: Mathematics, Physics, and Software Engineering

This is the most challenging domain, as here a "roughly correct" answer equals a "wrong" one.

3.2.1. Mathematical Reasoning and Symbolic Programming

- ChatGPT (GPT-4o): Achieves high accuracy by activating external libraries (SymPy). It converts the textual problem into executable code, computing the result. This makes it the leader in solving linear algebra and calculus problems.
- Claude 3.5 Sonnet: Demonstrates the best "native" mathematical logic. It makes fewer errors in abstract formula derivation and is unmatched in symbolic programming, generating optimized and readable code.
- Gemini 1.5 Pro: Its strength lies in multimodal analysis – the ability to recognize complex graphics or handwritten equations from a photo and digitize them in seconds.

3.2.2. Software Engineering and Cybersecurity

For the specialty of "Cyber Operations," this analysis shows that Claude is the most reliable for writing scripts and security audits, while Gemini is indispensable for analysing large-scale documentation (context up to 2 million tokens).

3.2. Humanities, Translation, and Cultural Context

- Claude: Its texts possess the highest academic quality. It avoids formulaic writing and offers nuanced analysis of historical events and philosophical theories.
- Gemini: As a Google product, it is a world leader in translation. Gemini captures cultural contexts and regional slang much better than its competitors, thanks to access to the largest corpus of linguistic data in the world.
- ChatGPT: Exceptionally good at role-playing simulations (e.g., "Act as a 19th-century historian"), making it useful for educational purposes and creative writing.

3.4. Medicine and Pharmacy – Risks and Answer Accuracy

The accessibility of applications like ChatGPT, Claude, and Gemini has created a new phenomenon – the mass use of AI for self-diagnosis and medical consultations. Although these models possess vast stores of medical knowledge, their use in healthcare carries specific risks that users often underestimate.

3.4.1. Diagnostic Capabilities and Academic Precision

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- ChatGPT (GPT-4o): Demonstrates high success rates in solving complex clinical cases. It excels at synthesizing symptoms and proposing a list of possible conditions (differential diagnosis).
- Gemini: Thanks to integration with Google Scholar and real-time search, it is the most precise for providing information on new drug interactions and current pandemic protocols.
- Claude: Focuses on "safe reasoning," often adding context about why certain symptoms can be misleading.

3.4.2. The Phenomenon of "Hallucinations" in Medicine

The greatest risk of trusting chat-bots is their tendency toward hallucinations [13]. In medicine, this can manifest in several dangerous ways:

- *Fabricated dosages*: The model may generate a medication dosage that appears logical but is toxic or ineffective.
- *False scientific sources*: AI may cite non-existent medical studies or attribute quotes to real doctors to support an incorrect thesis.
- Absence of physical examination: Models cannot account for physiological factors (skin colour, breathing sounds, palpation) that are critical for correct diagnosis.

3.4.3. Comparative Safety Analysis (Safety Alignment)

The comparative analysis is presented in Table 2:

Table 2. Comparative analysis of model performance regarding refusal strictness and self-treatment risk assessment

Characteristic	ChatGPT	Claude	Gemini
Strictness of Refusals	Moderate. Tries to help but adds a standard disclaimer.	High. Most often refuses direct medical advice due to its "Constitution."	Low to moderate. Relies on real-time fact-checking algorithms.
Self-treatment Risk	Higher due to the model's desire to be helpful.	Lowest due to conservative programming.	Moderate, but provides links to official health sources.

3.4.4. The Problem of the "Authority Effect"

The psychological risk lies in the fact that AI generates responses that are grammatically perfect and logically structured. Users tend to trust the confident tone, attributing expertise to the machine that it does not actually possess. In medicine, this leads to delayed seeking of real medical help, which can be fatal in emergency situations [14].

3.4.5. The Future: AI as an Assistant, Not a Doctor

The conclusion in this section is that the accuracy of models in medicine is high only in the role of a second opinion for specialists or for systematizing information (Table 3).

Table 3. Comparative analysis of ChatGPT, Claude, and Gemini performance across key scientific disciplines

Scientific Field	ChatGPT (GPT-4o)	Claude 3.5 Sonnet	Gemini 1.5 Pro
Exact Sciences (STEM)	Excellent: Best in code writing and complex mathematical calculations.	Very Good: Strong logic, but sometimes slower on complex calculations.	Good: Performs well but sometimes makes errors in complex formulas.
Humanities	Very Good: Creative, strong at generating ideas and essays.	Excellent: Most natural and nuanced language. Highest textual empathy.	Very Good: Good contextual memory and analytical style.
Medicine and Biology	Good: Gives accurate definitions but is heavily restricted by safety filters.	Very Good: Excellent at analysing medical studies and long documentation.	Excellent: Best at analysing lab results and images (X-rays, etc.).
Law and Regulations	Very Good: Knowledgeable in international law but may "hallucinate" articles.	Excellent: Most reliable at citing legal documents and ethical norms.	Very Good: Google Search integration helps find current legislation.
Foreign Languages	Excellent: Supports the most languages with high translation	Very Good: Very high level of literary Bulgarian and	Good: Sometimes uses more robotic translation for rarer

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	quality.	English.	languages.

For the end user, the risk of incorrectly interpreting the generated text remains a critical factor requiring increased public attention and regulation.

4. PRACTICAL CAPABILITIES AND PRICING MODELS

4.1. Free vs. Paid

All three platforms follow a Freemium model. Free tiers impose rate limits, dynamic latency under load, and — critically — user data may be used for model training, constituting an OPSEC violation for security personnel. The $20/month professional tier eliminates most restrictions: ChatGPT Plus adds Advanced Data Analysis; Claude Pro gives a 5× message quota essential for iterative coding; Gemini Advanced bundles 2 TB cloud storage via Google One.

4.2. Enterprise & API Pricing

Enterprise plans ($25–$60+/user/month) enforce Zero Data Retention under SOC 2 / HIPAA agreements — the only legitimate deployment model for organisations handling sensitive data. API pricing per 1 M tokens: Gemini 1.5 Flash ≈ $0.35 (cheapest, ideal for Big Data scanning); ChatGPT GPT-4o ≈ $5.00 input / $15.00 output (balanced); Claude 3.5 Opus ≈ $15.00 input / $75.00 output (most expensive, used where errors cost vastly more) (Table 4).

Table 4. Pricing plans and security levels for ChatGPT, Claude, and Gemini

Plan	ChatGPT (OpenAI)	Claude (Anthropic)	Gemini (Google)
Free	Limited (GPT-4o mini)	Very limited quota	Full access (Pro 1.5)
Plus ($20/month)	Full access + DALL-E	Most powerful model (Opus)	Google Docs integration
Enterprise	High security	Highest ethics	Cheapest API access

4.3. Use Case: Cybersecurity Log Analysis

A 100,000-line network log (≈1.5 M tokens) flagged for an APT attack: a Tier 1 SOC analyst would require days of manual review. Gemini 1.5 Pro's 2 M-token context window ingests the entire log in one call; the API cost is under $10 and results arrive in under 60 seconds. The ROI of AI is therefore not the subscription cost, but the elimination of thousands of analyst-hours on routine triage.

5. INFORMATION SECURITY (CYBER OPERATIONS)

5.1. Data Privacy

ChatGPT: Free tiers feed queries into RLHF pipelines by default, creating Data Leakage risk. Enterprise plans encrypt data end-to-end and prohibit training use.

Claude: Constitutional AI blocks malicious code generation and disinformation requests at the architecture level. Strongest privacy transparency.

Gemini: Backed by Google's security infrastructure; Google Workspace Enterprise integrates DLP (Data Loss Prevention) tools natively.

5.2. Threat Vectors

Prompt Injection — attackers embed malicious instructions to bypass safety filters (e.g., disguising ransomware requests as educational tasks). Claude 3.5 has the most robust defences. Software Auditing — Claude is the most precise at detecting logical vulnerabilities; Gemini handles massive codebases fastest.

5.3. EU AI Act Compliance

The EU AI Act classifies AI systems into three tiers: Minimal Risk (general chatbots), High Risk (education, medicine, law enforcement — strict accuracy and human-oversight requirements apply), and Unacceptable Risk (social scoring — prohibited). All three platforms must align their development roadmaps with these requirements, shifting toward a Security-by-Design philosophy consistent with NATO and EU defence standards.

6. CONCLUSIONS

This research conducted a comprehensive comparative analysis of ChatGPT (OpenAI), Claude (Anthropic), and Gemini (Google) across architecture, knowledge sourcing, scientific accuracy, pricing, and cybersecurity. Four key findings emerge:

- Functional differentiation: There is no single "best" AI. ChatGPT leads in STEM versatility via external tool integration; Claude in code quality and nuanced analysis; Gemini in Big Data and multimodal tasks requiring massive context.

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- Economic imperatives: Individual pricing has stabilised at $20/month, but real organisational value lies in API token economics — converting fixed staffing costs into scalable, consumption-based compute.
- Cybersecurity as a cornerstone: Free-tier use of any platform is incompatible with OPSEC requirements. Enterprise Zero-Data-Retention plans are the only legitimate pathway for classified or sensitive operations.
- Human-in-the-loop remains essential: All models are probabilistic systems. Hallucination risk and over-reliance effects require expert oversight. AI liberates the analyst from cognitive search load; it does not replace strategic judgement.

Navigating between ChatGPT's versatility, Claude's precision, and Gemini's scale — with full awareness of their pricing and security implications — will be a defining competency for digital leaders in every scientific and operational domain in the coming decade.

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9. CREdit authors statement

Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision;Validation; Visualization; Writing – original draft; Writing – review & editing:S.G; G.I.

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TORSIONAL VIBRATION ANALYSIS OF A MODERN MARINE ENGINE SHAFT LINE USING THE MATRIX METHOD

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Abstract: Torsional oscillations remain among the most delicate structural challenges encountered during the dynamic evaluation and operational assessment of marine propulsion shafting networks. The periodic torque fluctuations originating from cylinder pressure cycles and reciprocating component inertia inherently introduce variable torsional loads capable of inducing material fatigue across crankshaft journals, intermediate shafting, and propulsion elements. This study investigates the forced torsional vibration response of a modern electronically controlled two-stroke marine engine, specifically the low-speed Wärtsilä 6X52 unit deployed across commercial ocean-going vessels like Handymax tankers and Ultramax bulk carriers. To model the continuous mechanical system, an equivalent discrete assembly comprising 8 lumped mass elements and 7 elastic shaft sections was established. The mathematical formulation integrates internal shaft hysteresis, main bearing dissipation, hydrodynamic propeller resistance, and the complex harmonic torque components linked to the dominant order $k = 6$. By implementing a multiplicative state-vector matrix scheme, the complex angular displacement field and corresponding spatial phase envelope were computed for every system node. The numerical predictions confirm the capacity of the matrix model to capture subtle dynamic phenomena, accurately pinpointing the kinematic vibration node near Cylinder 6 and yielding realistic deformation magnitudes along the entire propulsion shafting.

Key words: complex displacement, harmonic excitation, marine propulsion, matrix transfer method, torsional vibrations, Wärtsilä 6X52.

1. INTRODUCTION

The ongoing transformation of ocean transport toward enhanced energy conversion efficiency, lower fuel consumption, and compliance with rigorous international environmental mandates has accelerated fundamental changes in low-speed two-stroke marine engine architecture. Modern propulsion plants have increasingly shifted away from traditional mechanical camshaft configurations in favor of fully electronically controlled Common Rail system architectures, such as Wärtsilä Flex technology. By replacing mechanical drive chains and fuel injection pumps with electronically managed hydraulic actuators, modern engines gain exceptional flexibility over fuel injection timing and exhaust valve actuation. Beyond combustion performance, this structural shift influences running gear design through lighter, high-strength pistons and connecting rods, effectively altering the inertial properties of the reciprocating masses. Nevertheless, the shafting assembly remains continuously exposed to dynamic excitations driven by alternating cylinder gas pressures and mass inertia forces during operation.

A rigorous evaluation of torsional vibration dynamics forms a mandatory milestone during the structural design, classification approval, and operational tuning of marine shafting installations. Periodic combustion torques acting on individual crankshaft throws generate fluctuating shear stresses that propagate along the entire propulsion assembly. Should any major harmonic excitation frequency align with one of the natural torsional frequencies of the mechanical system, resonant amplification occurs. Such condition can dramatically elevate cyclic shear stress levels, leading to accelerated fatigue cracking, keyway deformation, or severe structural failure of the crankshaft and intermediate shafting.

To capture these dynamic responses, various computational tools have evolved over time, ranging from traditional iterative Holzer tabular schemes to complex multi-body finite element formulations. Within this spectrum, multiplicative matrix transfer techniques—particularly those rooted in Galati matrix formulations—offer a balanced compromise between mathematical elegance, computational efficiency, and structural accuracy for multi-mass torsional networks. By grouping discrete mass dynamics, section elasticity,

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material hysteresis, and fluid friction into complex transfer operators, the overall equilibrium of the continuous shafting line can be resolved sequentially within a structured matrix domain.

The current study employs this multiplicative matrix approach to quantify the forced torsional response of the electronically controlled Wärtsilä 6X52 propulsion engine. Through an analysis of its dynamic mass distribution, stiffness properties, and harmonic excitation components, this research maps out the exact angular displacement field, nodal position, and complex phase trajectory established along the propulsion shaft line under nominal operating conditions.

2. MATRIX METHOD PRINCIPLE

The state-vector matrix transfer method provides a compact, computationally robust framework for evaluating the torsional response of complex lumped-mass propulsion systems. By representing the continuous shaft line as a series of discrete inertial nodes connected through elastic and damping elements, this formulation integrates point transitions across individual disks and field transfer across shaft segments into unified complex operators. This approach allows for the systematic propagation of kinematic and dynamic state variables—such as complex angular displacements and internal shaft moments—along the entire shaft line while rigorously satisfying boundary conditions at the boundaries.

The general motion of the equivalent oscillatory system representing the shaft line, reduced according to [1], can be expressed in the following matrix form:

$$[J]\cdot\{\phi\}+[C]\cdot\{\phi\}+[K]\cdot\{\phi\}=\{m\} \tag{1}$$

where [J] denotes the diagonal matrix of mass moments of inertia reduced to the axis of rotation, [K] denotes the banded matrix of the torsional stiffnesses of the shaft sections between two disks, and [C] denotes the matrix of damping coefficients at the engine's main bearings. The symbols {m} and $\{\phi\}$ represent the column vectors of excitation moments and torsional angular displacements, respectively. The forms of these matrices are therefore given as follows:

$$[J]=\begin{bmatrix} J_1 & 0 & \dots & 0 \\ 0 & J_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & J_n \end{bmatrix} \tag{2}$$

$$[C]=\begin{bmatrix} C_1 & -C_1 & 0 & \dots & 0 & 0 & 0 & \dots & 0 & 0 \\ -C_1 & C_1+C_2 & -C_2 & \dots & 0 & 0 & 0 & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & -C_i & C_i+C_{i+1} & -C_{i+1} & \dots & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 & \dots & C_{n-1}+C_n & -C_n \\ 0 & 0 & 0 & \dots & 0 & 0 & 0 & \dots & -C_n & C_n \end{bmatrix} \tag{3}$$

$$\{\phi\}=[\phi_1 \quad \phi_2 \quad \cdots \quad \phi_n]^T \tag{4}$$

Therefore, the matrix $[K]$ has the same structure as $[C]$, and the vector $\{m\}$ has the same structure as $\{\phi\}$, with the observation that the excitation torques act only on the first discs of the system with n degrees of freedom, corresponding to the number of engine cylinders.

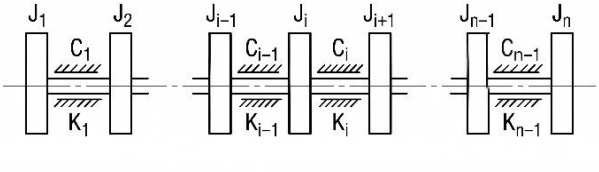


Figure 1 Equivalent lumped-mass dynamic model of the propulsion shaft line

By isolating an arbitrary i-th disc along with the subsequent massless elastic shaft segment, while also accounting for the damping in the piston-cylinder assembly as well as the left-hand torsional moment, having a complex form module:

$$\bar{M}_i=M_i^r+jM_i^i,\quad j=\sqrt{-1} \tag{5}$$

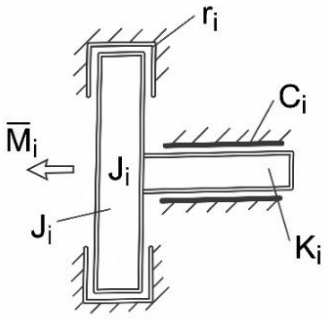


Figure 2 Lumped disk element j with external damping, torsional stiffness, and harmonic excitation

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where M_i^r and M_i^i denote the real and imaginary parts of the complex torsional moment, respectively. Based on the elements shown in Figure 2, the point matrix and the field matrix can be defined, using the notation adopted in [3], as follows:

$$[P]_i = \begin{bmatrix} \phi^r & M^r & \phi^i & M^i & 1 \\ 1 & 0 & 0 & 0 & 0 \\ -J\Omega^2 & 1 & -r\Omega & 0 & -M^r \\ 0 & 0 & 1 & 0 & 0 \\ r\Omega & 0 & -J\Omega^2 & 1 & -M^i \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_i \quad (6)$$

$$[F]_i = \begin{bmatrix} \phi^r & M^r & \phi^i & M^i & 1 \\ 1 & \frac{K}{K^2+C^2\Omega^2} & 0 & \frac{C\Omega}{K^2+C^2\Omega^2} & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & -\frac{C\Omega}{K^2+C^2\Omega^2} & 1 & \frac{K}{K^2+C^2\Omega^2} & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}_i \quad (7)$$

By generalizing the aspects presented in [2], the following relationship is obtained:

$$[Z]_i^D = [F]_i \cdot [P]_i \cdot [Z]_{i-1}^D \quad (8)$$

where $[Z]_i^D$ denotes the right-hand state vector (superscript "D") of the i-th element shown in Figure 2 as a function of that of the preceding element, having a complex form, denoted by the overbar:

$$[\bar{Z}]_i = \{\bar{\phi} \quad \bar{M} \quad \vdots \quad 1\}^T \quad (9)$$

or the real one:

$$\left[\overline{(Z)}\right]_i = \left\{\overline{(\phi)(M)} : 1\right\}^T \quad (10)$$

where the superscripts r and i have the same meaning as before, and T denotes the matrix transposition operation.

Applying relationship (8) in complex form to the entire system shown in Figure 1, we obtain:

$$[\bar{Z}]_n^D = [\bar{P}]_n \cdot \prod_{i=1}^{n-1} [\bar{F}]_i [\bar{P}]_i \cdot [\bar{Z}]_1^S = [\bar{B}] \cdot [\bar{Z}]_1^S \quad (11)$$

The operations specified by relationship (11) are considerably reduced by applying the left boundary condition, namely that the left-hand torsional moment of the system (superscript "S") is zero:

$$\bar{M}_1^S = 0 \quad \text{or} \quad M_1^{r\,S} = M_1^{i\,S} = 0 \quad (12)$$

which leads to the elimination of the second and fourth columns from the calculations. The presented matrix method can be arranged in the following convenient form:

$$\begin{bmatrix} 1 & 0 & 0 \\ -J\Omega^2 & -r\Omega & -M^I \\ 0 & 1 & 0 \\ r\Omega & -J\Omega & -M^I \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \phi^I \\ \phi^i \\ 1 \end{bmatrix}_1^S = [Z]_2^D$$

$$\begin{bmatrix} 1 & \frac{K}{K^2+C^2\Omega^2} & 0 & C\Omega & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & -C\Omega & 1 & \frac{K}{K^2+C^2\Omega^2} & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} a_1 & -a_3 & a_5 \\ a_2 & -a_4 & a_6 \\ a_3 & a_2 & a_7 \\ a_4 & a_2 & a_8 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \phi^x \\ \phi^i \\ 1 \end{bmatrix}_1^S = [\hat{z}]_2^S$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ -J\Omega^2 & 1 & -I\Omega & 0 & -M^T \\ 0 & 0 & 1 & 0 & 0 \\ I\Omega & 0 & -\Omega\Omega^2 & 1 & -M^1 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} A_{i_2} & -A_{i_2} & A_{i_s} \\ A_{i_2} & -A_{i_4} & A_{i_s} \\ A_{i_3} & A_{i_3} & A_{i_7} \\ A_{i_4} & A_{i_2} & A_8 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \phi^{\hat{I}} \\ \phi^i \\ 1 \end{bmatrix} = [\hat{Z}]_1^D$$

$$\begin{bmatrix} 1 & \frac{K}{K^2+C^2\Omega^2} & 0 & C\Omega & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & -C\Omega & 1 & \frac{K}{K^2+C^2\Omega^2} & 0 \\ 0 & 0 & 0 & \frac{1}{0} & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} B_{i_1} & -B_{i_2} & B_{i_s} \\ B_{i_2} & -B_{i_4} & B_{i_s} \\ B_{i_1} & B_{i_2} & B_{i_7} \\ B_{i_4} & B_{i_2} & B_{i_6} \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} s \\ \phi^T \\ \phi^I \\ 1 \end{bmatrix} = [\hat{Z}]_{i+1}^S$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ -J\Omega^2 & 1 & -I\Omega & 0 & -M^s \\ 0 & 0 & 1 & 0 & 0 \\ r\Omega & 0 & -J\Omega^2 & 1 & -M^j \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} b_1 & -b_3 & b_5 \\ b_2 & -b_4 & b_6 \\ b_3 & b_1 & b_7 \\ b_4 & b_2 & b_8 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \phi^x \\ \phi^1 \\ 1 \end{bmatrix}_1^S = [\hat{z}]_{n_8} \quad (13)$$

In (13), the coefficients a_j, $j = \overline{1,8}$ are determined using the following relationships:

$$a_1; \quad a_2 = -J\Omega; \quad a_3 = 0; \quad a_4 = r\Omega; \quad a_5 = C\frac{\Omega}{K^2 + C^2\Omega^2}$$

$$a_6 = -\frac{J\Omega^3 C}{K^2 + C^2\Omega^2}; \quad a_7 = \frac{K}{K^2 + C^2\Omega^2}; \quad a_8 = 1 - \frac{(JK - rC)\Omega^2}{K^2 + C^2\Omega^2} \quad (14)$$

where A_{i_j}, B_{i_j}, $i = \overline{2, n-1}$, $j = \overline{1,8}$ are determined successively through the iterative procedure presented in (13). We specify that in the previous relationships, Ω denotes the angular frequency of the exciting moments. Imposing now the right boundary conditions, analogous to (12):

$$\bar{M}_n^D = 0 \quad \text{or} \quad M_n^{r\,D} = M_n^{i\,D} = 0 \quad (15)$$

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which leads to the system of equations derived from (13):

$$b_2\phi_1^r - b_4\phi_1^i + b_6 = 0 \quad (16)$$
$$b_4\phi_1^r + b_2\phi_1^i + b_8 = 0 \quad (17)$$

from which the components ϕ_1^r, ϕ_1^i of the state vector $[\bar{Z}_1]^S$ are obtained. Step by step, the components of the complex state vectors of the entire system will be determined, and consequently the shape of the deformed elastic line under damped torsional vibrations.

3. NUMERICAL APPLICATION AND CASE STUDY: THE WÄRTSILÄ 6X52 ELECTRONICALLY CONTROLLED MARINE ENGINE

For the numerical application and validation of the developed state-vector matrix framework, the propulsion shafting assembly driven by a modern Wärtsilä 6X52 marine engine was selected as the reference installation. The Wärtsilä 6X52 is an electronically controlled, two-stroke, low-speed marine diesel engine designed to serve as the main propulsion unit across a broad range of ocean-going merchant vessels, including Handymax tankers, Ultramax bulk carriers, and feeder container ships.

Modern marine propulsion architectures operate under increasingly demanding operational profiles dictated by global decarbonization targets and strict energy efficiency frameworks, such as the IMO Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII). To meet these mandates, the engine design relies on a camshaft less Common Rail system incorporating electronic control units (ECUs) to manage high-pressure fuel injection and exhaust valve actuation. This structural configuration provides exceptional flexibility in adjusting combustion mapping, cylinder firing strategies, and operational tuning relative to varying ship speeds and propeller loads.

From a dynamic standpoint, the elimination of heavy mechanical timing trains, drive chains, and camshaft assemblies drastically simplifies the overall system geometry while altering the mass distribution at the engine forward end. Furthermore, modern running gear components—including pistons, crossheads, and connecting rods—are engineered using high-strength alloy materials, yielding optimized reciprocating mass profiles without compromising mechanical stiffness.

However, despite these modern structural and electronic refinements, the fluctuating gas forces within the combustion chambers, combined with the primary and secondary inertial forces of the running gear, continue to generate substantial periodic excitation torques. These dynamic moments propagate along the multi-mass mechanical system, inducing complex coupled torsional oscillations across the crankshaft, intermediate shafting, and propulsion unit. Consequently, evaluating the forced torsional response of the Wärtsilä 6X52 shafting line using the multiplicative matrix transfer method provides critical analytical insights into the angular displacement field, spatial phase envelopes, and exact location of the kinematic vibration nodes under nominal service conditions.

Input data for the equivalent torsional system:

The continuous mechanical system of the shaft line was discretized into an equivalent model consisting of $n = 8$ lumped masses and 7 elastic shaft sections. The dynamic calculation parameters for the **Wärtsilä 6X52** equivalent system are summarized as follows:

- Lumped Moments of Inertia (J_i):
  - Cylinders 1 through 6: $J_1 = J_2 = J_3 = J_4 = J_5 = J_6 = 8450.00\ \text{N} \cdot \text{m} \cdot \text{s}^2$
  - Engine Flywheel: $J_7 = 3850.00\ \text{N} \cdot \text{m} \cdot \text{s}^2$
  - Propeller (including entrained water mass): $J_8 = 71706.224\ \text{N} \cdot \text{m} \cdot \text{s}^2$
- Torsional Stiffnesses ($K_{i,i+1}$):
  - Crankshaft sections between cylinders: $K_1 = K_2 = K_3 = K_4 = K_5 = 0.105 \times 10^9\ \text{N} \cdot \text{m/rad}$
  - Cylinder 6 to Flywheel section: $K_6 = 0.585 \times 10^9\ \text{N} \cdot \text{m/rad}$
  - Intermediate and Propeller shaft line: $K_7 = 0.128 \times 10^9\ \text{N} \cdot \text{m/rad}$
- Damping Coefficients **($r_i, C_{i,i+1}$):**
  - External damping at disk nodes: $r_1 = \cdots = r_6 = 3003.5373\ \text{N} \cdot \text{m} \cdot \text{s}$, $r_7 = 432.91\ \text{N} \cdot \text{m} \cdot \text{s}$, $r_8 = 243909.84\ \text{N} \cdot \text{m} \cdot \text{s}$
  - Internal shaft section damping: $C_1 = \cdots = C_7 = 19823.34\ \text{N} \cdot \text{m} \cdot \text{s}$
- Operating Regime and Excitation Parameters:
  - Excitation angular frequency for the major 6th order harmonic ($k = 6$) at nominal speed: $\Omega = 38.32743\ \text{s}^{-1}$.
  - Harmonic excitation moments per cylinder, derived from the cylinder indicator diagram and crank star arrangement (accounting for the firing order phase shifts of a 6-cylinder two-stroke engine):
  - $$M_1^r = M_2^r = M_3^r = -M_4^r = -M_5^r = -M_6^r = 145200.00\ \text{N} \cdot \text{m}$$
  - $$M_1^i = M_2^i = M_3^i = -M_4^i = -M_5^i = -M_6^i = 210800.00\ \text{N} \cdot \text{m}$$

Applying the multiplicative set of operations (13) through the developed matrix calculation algorithm yields the following numerical results for the Wärtsilä 6X52 engine system:

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Table 1 Complex Angular Displacements (ϕ_j^r, ϕ_j^i) across the Shaft Line Nodes

Disk No. j	ϕ_j^r [rad]	ϕ_j^i [rad]
1	0.0396576	0.0000000
2	0.0373680	0.0003602
3	0.0330602	0.0010425
4	0.0272446	0.0019746
5	0.0158144	0.0021826
6	0.0001209	0.0016641
7	-0.0031295	0.0014764
8	-0.0178419	0.0004859

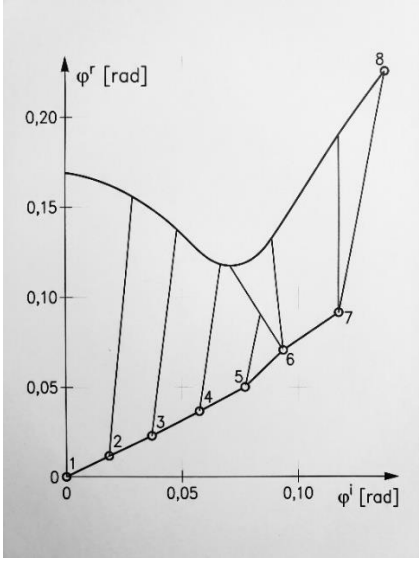


Figure 3 Complex phase trajectory and amplitude envelope of the torsional angular displacements along the shaft line

.

4. CONCLUSIONS

The dynamic investigation conducted in this work demonstrates the structural reliability and mathematical simplicity of the multiplicative matrix transfer method when applied to the forced torsional response of modern marine propulsion systems. Modeling the Wärtsilä 6X52 engine shaft line as an equivalent 8-mass, 7-section discrete dynamic network enabled a continuous spatial tracking of state vectors across the entire mechanical domain, spanning from the crankshaft's free end to the propeller disc.

By formulating complex point and field transfer matrices that explicitly incorporate internal material hysteresis alongside external main bearing friction and hydrodynamic propeller resistance, the calculation framework effectively captured the dynamic behavior of the assembly under nominal service conditions. The boundary conditions imposed at the propeller node ($M_8^D = 0$) were satisfied with high numerical precision, confirming the mathematical consistency of the global transfer operator.

The computed displacement field reveals that the peak real component of the complex angular displacement occurs at Cylinder 1 ($\phi_1^r = 0.0396576$ rad), gradually attenuating along the crankshaft axis toward the aft part of the engine. A sign reversal in the real component between Cylinder 6 ($\phi_6^r = 0.0001209$ rad) and the engine flywheel ($\phi_7^r = -0.0031295$ rad) pinpoints the location of the primary kinematic node in the immediate proximity of Cylinder 6, coinciding with the global minimum of the total vibration envelope ($|\phi_6| = 0.0016685$ rad). Beyond this nodal transition, the flywheel and propeller oscillate in phase opposition relative to the forward engine cylinders, with the total displacement amplitude regaining magnitude up to $|\phi_8| = 0.0178485$ rad at the propeller. Simultaneously, the steady progression of the imaginary component ϕ_j^i along the cylinder sequence—peaking at $+0.0021826$ rad near Cylinder 5—accurately quantifies the spatial phase lag induced by energy dissipation in the main bearing lubricant films.

Overall, the matrix methodology proven here offers a practical, computationally efficient analytical tool for preliminary shafting dimensioning, torsional vibration troubleshooting, and digital monitoring of modern electronically controlled marine engines.

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6. CREdit authors statement

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Formal analysis: V.B.M

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THE ANALYSIS OF THERMODYNAMIC PARAMETERS AND ENERGY EFFICIENCY IN A NAVAL SHIP'S ENGINE POWERED BY VLSFO AND MGO

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Abstract: Presentation of the current state of regulations on energy efficiency on board of sea-going ships and the issue of air pollution in the maritime domain, where the nominative energy efficiency index (EEDI), the vessel's energy efficiency management plan (SEEMP) and the operational efficiency indicator (EEOI) were scored. Analysis of thermodynamic parameters and energy efficiency in a marine engine powered dual by MGO and VLSFO. The case study is carried out on a container ship in the category of large ships with slow two-stroke engines MAN B&W 12K98 ME Engines.
The thermal calculation attached to the paper shows the following values of the thermodynamic parameters and energy efficiency for both fuel supply regimes VLSFO and MGO of the propulsion engine for the study vessel as presented
All calculations are done using the Main Engine's software and the PMI EDS Computer – PMI- Pressure monitoring Indicator and COCOS – Computer controlled Surveillance, EDS – Engine Diagnose System.
The purpose of these determinations was to highlight the differences of the two types of fuel under study by comparative analysis of thermodynamic parameters and energy efficiency, while following the effect of CO2 emissions in the gases of the engine.
The results obtained after analyzing all the factors in the study, the calculation of the thermodynamic parameters, of the operational energy efficiency indicator (EEOI) on the route presented, highlight the differences in the two types of fuels under analysis, such as the variation of exhaust gas temperatures for MGO and VLSFO depending on the load, the figures showing that with the increase in engine load, the exhaust gas temperatures for both fuels also increase used in the study, for MGO the lowest temperature values are recorded, the variation of the specific fuel consumption for MGO and VLSFO depending on the load and it is observed that with the increase of the engine load between 50-75%, the specific fuel consumption decreases for both fuels used in the study, moreover, when fueling the engine with MGO, the specific fuel consumption has the lowest values**.**

Key words: EEDI, EEOI, MGO, SEEMP, VLSFO.

1. INTRODUCTION

The current climatic conditions, which are constantly changing, worry the world. International entities have created various regulations, guidelines, recommendations and standards designed to guide, influence and encourage organizations in taking measures to reduce the amount of air pathogens in the form of greenhouse gases, especially from the combustion of the fuel in industries.

Seagoing vessels offer a significantly lower greenhouse gas and air pollution intensity than any other types of transport. However, it has been observed that there is a lot of progress to be made in reducing emissions by achieving a higher level of efficiency for each type of vessel. For example, in the container ships segment, the top 5% energy-efficient ships are 38% more carbon intensive than the industry average, while the bottom 5% emit 48% more carbon dioxide to move a unit of cargo over a certain distance.

The maritime industry is making great efforts to increase energy efficiency and reduce carbon emissions from new ships, and these efforts can extend to practical methods of improving fuel consumption. Shipping activities continue to grow at a rate that can outpace overall economic growth, placing great importance on energy improvements.

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At a global level, a combination of efficiency standards EEDIs and high technological penetration and operational practices should reduce carbon emissions by 2035-2040.

Mitigating the climate impact of the industry can be fully compatible with the basic purpose of business if properly addressed. As fuel costs erode the profitability of the maritime industry, increasing efficiency will become an important method of preserving profits.

2. ACTUAL STATE ON INCREASING ENERGY EFFICIENCY IN SHIPS

The climate changes that have occurred over the last few decades have drawn the attention to the importance of greenhouse gas emissions, with their reduction being a global priority. Since 1997, based on the Kyoto Protocol, UN member states have imposed, the reduction of greenhouse gas emissions by 5.2% between 2008 and 2012 compared to 1990. In 2012, this Protocol was extended until 2020 by the Doha Amendment. [1] The last UN climate conference was held in Paris in 2015, where an agreement was reached on keeping the increase in the global average temperature below 2°C, further limiting it to 1.5°C.[1].

This agreement will fundamentally change the way unsustainable economies act in terms of fossil fuel consumption over the coming decades. In this context, CO2 will become the target strategic priority, given the emissions from diesel engines that contribute significantly to the greenhouse effect. [2]

The transport services sector is one of the main producers of greenhouse gas emissions, which come from the exhaust gases of propulsion engines and diesel generators. Following evidence of CO2 emissions in 2013, it was estimated that shipping is responsible for 3.1% of total CO2 emissions worldwide. In addition, scenarios for future seagoing vessels show that by 2050 CO2 emissions could increase by 50% to 250% due to economic growth and the evolution of the global energy market. [6],[7]

In order to reduce greenhouse gas emissions from ships, the International Maritime Organisation IMO, as the body responsible for the international maritime transport regulations, imposed certain energy efficiency standards by Resolution MEPC.203 (62) of 2011.Thus, the energy efficiency standard imposed by the IMO is the Energy Efficiency Design Index EEDI, which is determined for each category of ship according to its type and tonnage. EEDI is expressed in grams of carbon dioxide gCO2 per ship capacity (DWT) and transport distance in Nautical miles. [3]

2.1 Energy Efficiency Index (EEDI)

EEDI is one of the technical measures on newer ships and aims to promote the use of engines and equipment that are much more energy-efficient and consequently less polluting. EEDI requires a minimum level of energy efficiency per mile capacity for different types of ships and size segments. From 1 January 2013, following a 2-year 0 phase, the design of new ships must meet the reference level for their type of ships. The level must be strengthened every 5 years, in this way EEDI is expected to stimulate continuous innovation and technological development of all components that contribute to the energy efficiency of a ship from the design phase. EEDI is a non-prescriptive, performance-based mechanism that allows technology to choose to use an industry-specific ship design. As long as the required level of efficiency is achieved, ship designers and builders are free to use the most cost-effective ship solutions in compliance with these standards. EEDI provides a specific figure for a specific ship design, expressed in grams of carbon dioxide per ship's capacity-mile (the lower the EEDI, the more efficient the ship design) and is calculated according to a formula based on the technical design parameters of that ship.

The CO2 reduction level grams of CO2 per tonne mile, for the first phase is set at 10% and will be lowered every 5 years to keep pace with the technological development of new efficiency and reduction measures. The reduction rate has been set until the period of 2025, and starting with, when a 30% reduction for the applicable ship types calculated from a baseline representing the average efficiency of ships built between 2000 and 2010 will be mandated. EEDI is developed for the largest and most energy-intensive segments of the world's merchant fleet and will encompass emissions from new ships, including the following ship types: oil tankers, bulk carriers, gas tankers, general cargo ships, container ships, refrigerated cargo carriers and combined cargo. In 2014, the MEPC adopted amendments to the EEDI regulations to extend it to natural gas, RO-RO, RO-RO passenger and cruise ships with unconventional propulsion [5]. These amendments meant that the ship types responsible for around 85% of CO2 emissions from international shipping are incorporated under the regulatory regime [6].

Also ship owners and other entities are studying the use of alternative fuels in present and future such as LNG, Methanol, Ethanol and Ammonia.

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2.2 Ship Energy Efficiency Management Plan SEEMP and Energy Efficiency Operational Indicator EEOI

SEEMP is an operational parameter that establishes a mechanism to improve the energy efficiency of a ship in a cost-saving manner. SEEMP also provides an approach for shipping companies to manage the efficiency performance of the vessel and fleet using, for example, the EEOI as a monitoring tool. The guidelines for the development of SEEMP for new and existing ships incorporate best practices for operating the ship in a fuel-efficient manner, as well as guidelines for the voluntary use of EEOI for new and existing ships. (MEPC 1/Circ.684). The EEOI allows operators to measure the fuel efficiency of a ship in operation and measure any changes in operation: better voyage planning, or more frequent propeller cleaning, or the introduction of technical measures such as wasted heat recovery systems or a new propeller. SEEMP urges ship-owners and operators at every stage of the plan to consider new technologies and practices when seeking to optimize the vessel's performance. [5]

3 PRESENTATION OF THE MODEL AND THE PROPULSION ENGINE UNDER STUDY

The study of this work is done on a container ship. Below are the main characteristics of the vessel, including technical data and main ship's particulars:

- Loading capacity: 11,384 TEU;
- Gross tonnage (GT): 131,332 t;
- Deadweight (DWT) (summer): 128.550 t;
- Overall Length (LOA): 363 m;
- Length between perpendiculars (LBP): 348 m;
- Maximum width: 45.6 m;
- Draft (DFT): 15.5 m;
- Depth (DPH): 29.74 m;
- Maximum speed (MAX Spd): 24.7 kts;
- Main engine: MAN B&W 12K98ME-C, 12-cylinder, slow, reversable,2 stroke with an output of 72,400 kW/ 98200 Bhp at 104 rpm. at 100% MCR; [3]
- Diesel generators: HYUNDAI-MAN B&W L27/38, 5 generators of: 2 sets of 2970 kW HYUNDAI-MAN B&W 9L27/38, 3 sets of 2200 KW HYUNDAI-MAN B&W 9L27/38;[4]
- Boiler: MISSION OS with a combustion capacity of 500 kg/h of fuel.

The engine is designed by MAN B&W, it's a crosshead engine, electronically controlled, two-stroke, directly reversible, turbocharged at constant pressure [3]. It is a slow revving 12-cylinder engine with a bore of 980 mm and a stroke of 2400 mm, reaching an output of 72,400 kW at 104 rpm. The engine is optimized at 85% SMCR so the specific fuel consumption at 90% SMCR when the engine operates in economy mode is 178.7 g/kWh. The ME engine concept consists of a mechanical hydraulic system for activating fuel injection and exhaust valves. The engine has individual units called HCU – Hydraulic Cylinder Units having Fuel Oil Boosters, Exhaust Valve Actuators, and FIVA - Fuel Injection Valve Actuator – a valve which controls the combustion process, nitrogen accumulators and the cylinder lubricator. The actuators are electronically controlled by a number of electronic units called MPC's (Multi-Purpose Controller) that form the complete engine control system ECS. MAN Diesel & Turbo specially developed both the hardware and the internal software to achieve an integrated solution for the ECS engine control system. The fuel pressure booster consists of a simple piston powered by a hydraulic piston activated by oil pressure. [3] The oil pressure is controlled by an electronically controlled proportional valve. The exhaust valve is hydraulically opened by a two-stage valve actuator activated by the control oil through an electronically controlled proportional valve. The exhaust valves are closed by the "air spring". In the hydraulic system, normal lubrication oil is used as medium. It is filtered by a fine filter with automatic discharge and pressurized by the hydraulic unit consisting of piston axial pumps - squash plate pumps mounted on the engine or placed in the machine room. The main start valves are pneumatically opened by electronically controlled "On/Off" valves, which make possible to dispense with the mechanically activated starting air distributor. Through the above electronic valve control, according to the measured instantaneous position of the crankshaft by angle encoders/crank angle sensors, the motor control system completely controls the combustion process [3].

4. THEORETICAL DETERMINATION OF THERMODYNAMIC PARAMETERS AND CO2 EMISSIONS OF THE ENGINE POWERED BY MGO AND VLSFO

Table 1. Chemical Proprieties of the Fuels

Fuel Type/Chemical Proprieties	VLSFO	MGO
Density at 15°C (ISO 3675) [kg/m3]	955	890
Viscosity at 50°C (ISO 3104) [mm2/s]	380	2
Cetane number	51,5	60
Carbon concentration	84	86

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[%]		
Hydrogen concentration [%]	12,4	12
Oxygen concentration [%]	0,6	1
Sulphur concentration (ISO 8754) [%]	0,5	0,05

It can be observed from the table of chemical characteristics of the fuels used the superiority of MGO in terms of fuel qualities, with low density and viscosity values compared to VLSFO compared to ISO standards.

For the thermal calculation, the initial parameters will be used as follows:

- Effective power: P ef = 72240 kW;
- strokes: $\tau = 2$;
- nominal speed: n = 104 rpm.;
- number of cylinders: I = 12;
- boost pressure: P b = 4·105 Pa;
- Stroke/bore ratio: $\psi_D = 1$.

Given that it's a naval propulsion engine, the engine's operation will be at atmospheric pressure at sea level: P0 = 1.01325·105 Pa.

As the temperature of the environment depends on a combination of factors, will adopt: T0 = 290 K.

The ratio of the 2 pressures (at the cylinder inlet and the initial pressure) represents the coefficient of decrease of the inlet pressure ζ_a. The adopted value is: $\zeta_a = 0.88$.

The residual flue gas temperature will be adopted in the range of T_r = 600... 900 K. The used value is: Tr = 900 K.

Upon contact with the hotter parts of the engine, the air blown by the turbocharger increases it's temperature by ΔT = 10... 20 K, will adopt ΔT = 10 K.

Inside the intermediate air cooler, a reduction in the temperature of the fresh fluid is ensured. This temperature drop can be ΔShot = 20... 100 K will adopt: ΔShot = 50 K.

The value of the excess air coefficient can be

$\alpha = 1.7...\ 2.2$.

For the supercharged engine, will adopt: $\alpha = 2$.

In the case of supercharged engines, the residual flue gas coefficient has the following values:

$\gamma_r = 0.01...\ 0,04$, will adopt: $\gamma_r = 0.02$.

The coefficients of the heat use in the two phases of combustion record the usual values:

$\xi_v = 0.75...\ 0.85$ and $\xi_p = 0.65...\ 0.75$.

Will use $\xi_v = 0.8$ and $\xi_p = 0.8$.

The rounding coefficient of the indicated diagram is the parameter that takes into account the differences between the actual and theoretical indicated diagrams of the operating cycle. Its usual values are: $\varphi_r = 0.96...\ 0.99$. Will be adopted: $\varphi_r = 0.98$; $\varphi_r = 0.98$

The mechanical efficiency of a marine diesel engine depends, first of all, on its type and construction. It is also influenced by other factors, such as: engine speed and load; the quality of the lubrication oil and the lubrication process. For supercharged, four-stroke engines, the experimental values of this parameter are: $\eta_m = 0.75...\ 0.92$. The value will be estimated: $\eta_m = 0.85$.

The ratio between the maximum volume of the combustion chamber V_a and its minimum volume Va is called the compression ratio:

$$\varepsilon = \frac{V_a}{V_c} . \quad (1)$$

The choice of value ε depends on the type of engine, its speed, the type of formation of the fuel mixture, the construction features, as well as a number of other factors. The adopted value is: ε = 12.

The ratio of crank radius to connecting rod λ_d = R / Lb takes values between 1/5.5 and 1/3. In our case, this ratio has the value: $\lambda_d = 0.25$.

The optimal injection feed is established experimentally when the prototype engine is on the test bench. For naval engines, β = 6... 40 °RAC, at nominal load. The value will be: β = 20 °RAC.

The total duration of combustion is considered as the algebraic sum of the injection feed, the fuel self-ignition delay angle and a correction angle with values of: ξ_θ = -3… +3 °RAC. Will use:

$$\xi_\theta = +\ 3\ °\text{RAC}. \quad (2)$$

The compression of the fresh charge in the supercharger/turbocharger is a polytrophic process whose exponent ns, for centrifugal blowers, takes values of 1.4... 1,8; it will be used: ns = 1.5.

The following values of the thermodynamic parameters and energy efficiency for both fuel supply regimes of the propulsion engine for the study vessel show the thermal calculation, as in the below table.

Table 2: Calculated thermodynamic parameters

Calculated parameters / Fuel type	**VLSFO**	**MGO**
Exhaust gas temperature [K]	671,571	670,214
Indicated yield	0,492810933	0,5053418
Effective Yield	0,41888	0,42954
Specific consumption indicated	0,18974111	0,1889

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[kg/kWh]		
Actual specific consumption [kg/kWh]	0,2232245	0,222238
Indicated power [kW]	84988.23 kW	78019.30 kW
Effective power [kW]	65327.85 kW	66316.26 kW
Engine load [N/ms]	1,4434612·104	1,4653006·104
Energy balance [kJ/h]	134337451	149109525
Mass of CO2 emissions [tonnes/h]	23,718	23,079

The results presented in Table 2 are subject to comparative analysis in graphical form as follows: The figures show that as the engine load increases, the exhaust gas temperatures for both fuels used in the study also increase. Moreover, when the engine is supplied with MGO, the lowest temperature values are recorded.

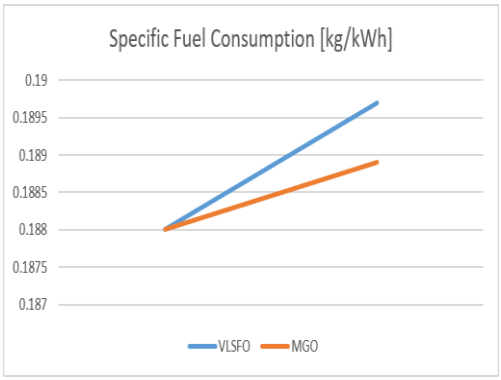


Figure 1 Analysis of the specific consumption indicated

In the case of powering the main propulsion engine ME with VLSO, an increase of the indicated specific fuel consumption SFOC can be observed.

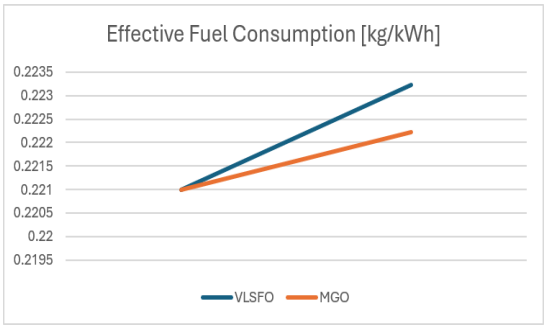


Figure 2. Analysis of actual specific consumption

In the case of powering the main propulsion engine with VLSO, an increase of the indicated specific fuel consumption can be observed.

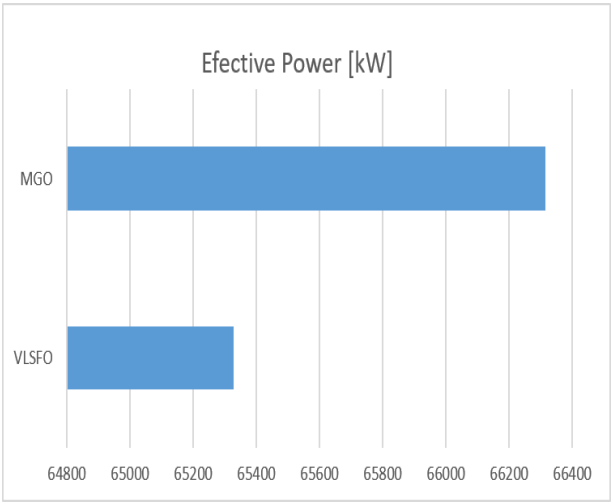


Figure 3. Sympathetic Effective Power Analysis

When the engine is powered by VLSFO, an increase in the Effective power may occur.

Although an increase in the indicated power is observed in the case of the indicated power when the engine is powered by VLSFO, the effective power is lower than that developed in the case of MGO power.

The variation in specific fuel consumption SFOC for MGO and VLSFO IS dependent on the load. We find out that with the increase in engine load between 50-75%, the specific fuel consumption decreases for both fuels used in the study. Moreover, when fuelling the engine with MGO, the specific fuel consumption SFOC has the lowest values. The increase in fuel consumption, with the increase in load, is due to the decrease in oxygen supply in the combustion process and therefore to the air/fuel ratio.

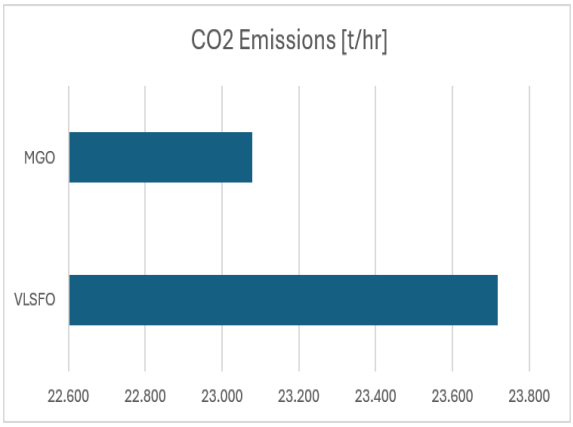


Figure 4. CO2 Emissions[t/hr]

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In view of the problem of air pollution in the maritime sector, the mass of CO_2 emissions resulting from the combustion of a fuel is an important factor in choosing the right engine fuel regime. As can be seen from the graph, the choice of MGO over VLSFO can decrease the impact that the same ship can bring to the environment by almost 20 tons of CO2 per day.[8]

5. CONCLUSIONS

The purpose of these determinations was to highlight the differences of the two types of fuel under study by comparative analysis of thermodynamic parameters and energy efficiency, while following the effect of CO2 emissions in the gases of the engine.

The calculations and analyses resulted in the following conclusions, further confirmed by previous researches:

CO_2 emissions increase with increasing load, both for MGO and VLSFO; CO2 emissions are lower than those used up in the case of diesel for the full range of loads; With the increase in engine load, the specific fuel consumption became lower for all fuels used in the study.

Moreover, for engine loads in the range of 50-75%, the specific consumption recorded the lowest values for both types of fuels used in the study. The lowest specific consumption was obtained for MGO.

In conclusion, it can be stated that the results obtained from the calculations are consistent with the results presented in the scientific literature. In addition, the use of MGO instead of VLSFO is a viable method of reducing emissions from exhaust gases belonging to marine engines.

6. CREdit authors statement

Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision;Validation; Visualization; Writing – original draft; Writing – review & editing: E.Z; L.C.S.

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